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LIMNOLOGICAL AND FISHERIES EVIDENCE
FOR AREA LIMITATION OF SOCKEYE
PRODUCTION IN FALLS LAKE,
NORTHERN SOUTHEAST ALASKA (1981 - 1982)

BY
J. P. Koenings
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January, 1984

PART I: Falls Lake Fisheries Program

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ABSTRACT

During 1981 and 1982, pre-fertilization studies were conducted at Falls Lake to determine primary, secondary and tertiary production patterns prior to lake enrichment. This portion of the report summarizes the tertiary production studies which emphasized in-lake growth, and smolt and adult population characteristics of sockeye salmon, *Oncorhynchus nerka*.

Sockeye smolts were found to be relatively small in both 1981 and 1982. For example, age 1.0 smolts averaged 68 mm in length, and age 2.0 smolts averaged 84 mm in length in 1981 with both age groups somewhat smaller in size in 1982. In addition, within-lake growth patterns, as revealed by late fall tow samples, and subsequent smolt production indicated that age 2.0 smolts were a significant proportion of the outmigration, ranging from 40% of the total in 1981 to 83% of the total in 1982. Consistent with this pattern is the freshwater age of returning adults, i.e., from 47% to 60% of the fish had reared for two years or longer in Falls Lake. Finally, the adult age structure indicated an approximate 50:50 ratio between two-ocean and three-ocean fish. In 1982, three-ocean adults represented 37% of the escapement compared to a 57% representation in 1981.

In addition to the anadromous sockeye salmon, coho salmon, *O. kisutch*, smolts and adults were enumerated as was the native population of Dolly Varden, *Salvelinus malma*. Threespined sticklebacks, *Gasterosteus aculeatus*, were found in the lake; however, rainbow trout, *Salmo gairdneri*, were not observed to be present either in the lake or in the outlet stream.

Key Words: Tertiary production, lake enrichment, sockeye, coho, smolt emigration, adult immigration, age composition, char, and rearing juvenile.

INTRODUCTION

Lake enrichment as a sockeye salmon, *Oncorhynchus nerka*, enhancement/rehabilitation technique involves the large scale perturbation of entire lake ecosystems by artificially altering nutrient levels. As such, it is necessary to follow the effect(s) of large scale applications of fertilizer from the changing nutrient pool through to the smolt stage of the target fish. To accomplish this detailed evaluation, lake systems are studied in detail for two years prior to any product application so that the 'before' condition can serve as a control from which the 'after' condition can be evaluated. However, such evaluation programs are often plagued by unexplained temporal variation which often masks cause-and-effect relationships, however direct they may be.

Variation, inherent in all biological manipulations, reaches its maximum in field sited projects where uniform conditions are difficult to achieve. Therefore, careful selection must be made of the ecosystems (lakes in the enrichment program) which provide the smallest source of undefinable variation in order to demonstrate and/or recognize a desired effect. That is, to be able to evaluate the effect of altering lake fertility (or changing rearing fry densities in the case of lake stocking) on the production of sockeye smolts, the central idea is to concentrate on the most discrete experimental unit possible: the individual lakes. However, even individual lakes are extremely complicated, so it is probable that only if the individual lakes are homogeneous enough to minimize the formation of discrete races of salmon; and 1) support a large percentage of beach spawners, 2) contain a small littoral zone which results in a single limnetically defined food source, 3) have a simple access to the sea, and 4) contain one (or few) discrete basins, can meaningful cause-and-effect relationships be recognized. Thus, most large scale manipulations dealing with fish stock enhancement demand careful selection of 'simple' ecosystems in order to maximize the likelihood of clear cut responses.

Falls Lake was chosen (Koenings and Barto 1981) as a candidate lake for the Northern Southeast, Alaska, lake enrichment program because of both its manageable size, and its compatibility with the Alaska Department of Fish and Game (ADF&G) guidelines for lake enrichment programs. Both the location and size of the lake provide for a controllable site for interpreting the process of nutrient enrichment from the application of fertilizer to the return of adult fish. Once this process is defined, the technique can be refined for application to larger sockeye salmon lakes with the added likelihood of a predictable response. Finally, Falls Lake serves as an analog to other nutrient poor lake systems in Southeast Alaska currently being stocked with coho fry. As such, the information gained from the Falls Lake project would be beneficial to both programs.

Study Site Description

Falls Lakes (ADF&G No. 109-20-013) is located on the east coast of Baranof Island (56° 49'N; 134° 42'W) in Southeast Alaska, and is within the confines of the South Baranof Wilderness Area managed by the U. S. Forest Service. The lake lies at an elevation of approximately 6.1 m, and has a surface area of 95 ha or 234 acres (for a further morphometric description of Falls Lake see Part II of this report).

MATERIALS AND METHODS

Rearing Fry Surveys

A tow net survey was conducted on 8 October 1981 to collect juvenile sockeye salmon at Falls Lake. However, due to a funding shortage, tow net surveys originally planned for Falls Lake were not conducted in 1982. A portable mid-water trawling system similar in design to that described by Gjernes (1979) was used to capture juvenile sockeye. The trawl measured 2.0 m by 2.0 m at the mouth and was 7.5 m long. The net consisted of 5.0 cm and 2.5 cm (stretch mesh) knotless nylon in the body, and 1.3 cm knotless nylon in the cod-end. A series of north-south trawls through the pelagic zone of Falls Lake were conducted at night at depths of 2.5 m, 5.0 m, 7.5 m, 10.0 m, and 15.0 m.

All captured juvenile sockeye were preserved in 10% formalin for later analysis, and the total sample was analyzed for age-weight-length data with each fish being weighed to the nearest 0.1 g and measured to the nearest millimeter. A scale sample was taken from the perferred area of each fish and placed on a labeled microscope slide. The scale slides were analyzed for scale patterns using a microfiche projector to determine the age of each fish.

Smolt Enumeration and Sampling

Smolt emigrating from Falls Lake were captured with fyke nets placed in the outlet stream of the lake (Figure 1). The nets measured 1.0 m square at the mouth and tapered to 0.15 m in diameter at the cod-end. A wooden holding-box (1.0 m x 1.0 m x 0.5 m) was attached to the cod-end of each fyke net to facilitate sampling.

In 1981, installation of the smolt sampling gear was completed by 22 April. A single fyke net was operated continuously until 8 June, except for a 48-hour period on 25-26 May, during which high water levels in the outlet stream prohibited sampling smolts. In 1982, smolt sampling was initiated on 3 May with a single fyke net; however, a second fyke net was installed on 10 May to increase the sampling effort. Thereafter, the sampling gear operated continuously until 23 June with no disruptions. The fyke nets were placed in strategic locations in the outlet stream to maximize the sampling effort and yet be operable during high water. The nets sampled the entire water column at each net location, but only sampled about 6% of the stream width.

The fyke nets were fished continuously throughout the sampling period, except for short down times when the nets were being repaired. The holding-boxes were monitored daily, or on a more frequent basis during the peak of the run, for total catch, species composition, mark recovery, and age-weight-length data. Representative subsamples of up to 40 sockeye

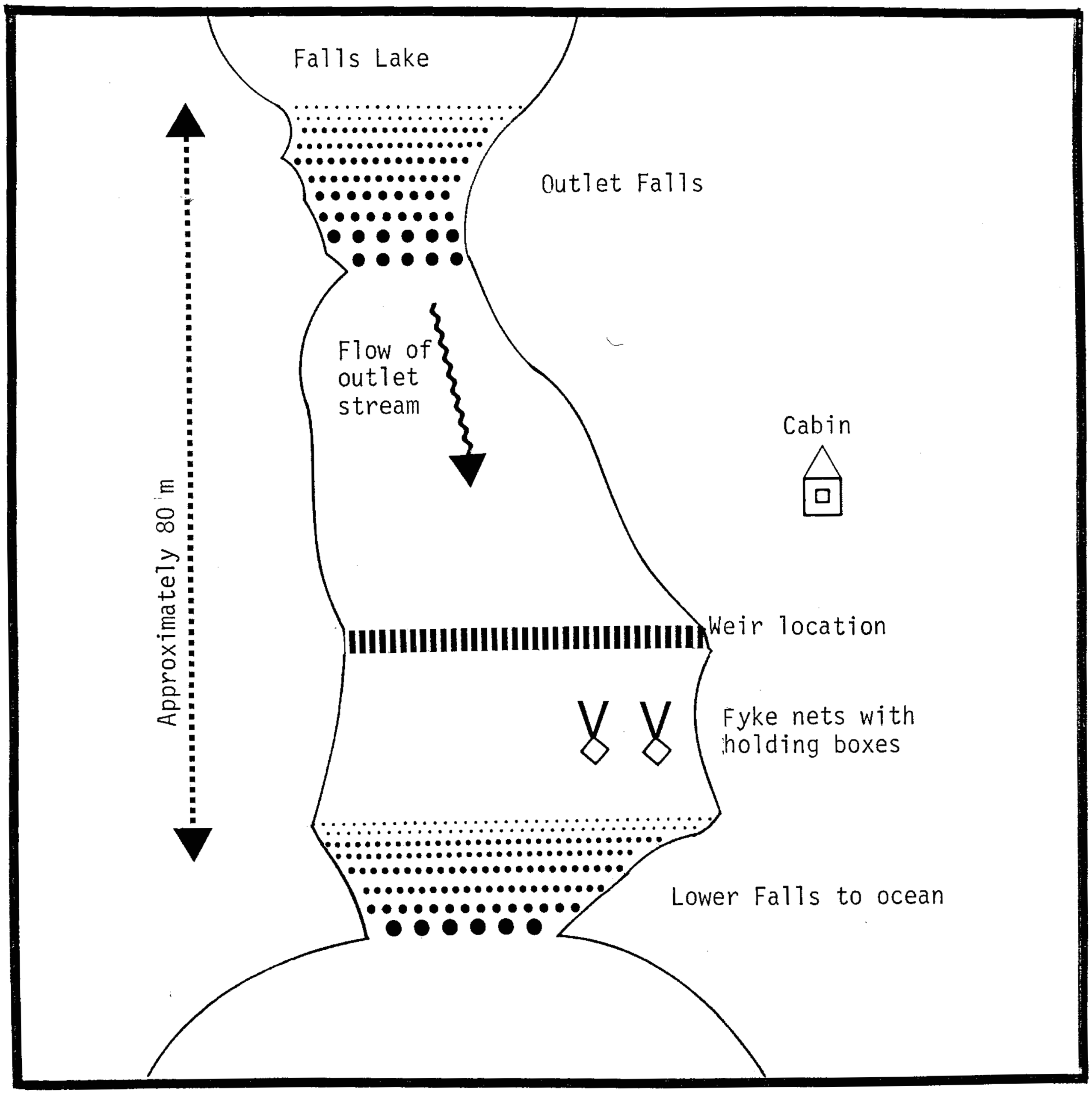


Figure 1. Schematic of the outlet of Falls Lake showing the location of the fyke nets used to capture sockeye and coho smolts, and the position of the picket weir used to enumerate returning adult fish.

smolts and 10 coho smolts were taken daily for age-weight-length data. If the total catch was less than 40 sockeye and 10 coho smolts, all fish caught were sampled.

Smolts subsampled for age-weight-length were anesthetized with MS-222, weighed to the nearest 0.1 gram, and measured to the nearest millimeter (fork length). Scales were removed from the preferred area and placed on labeled microscope slides. Data collected were organized such that all specific information could later be referred back to the source fish. All sampled smolts were allowed to recover in fresh water before being released downstream of the sampling apparatus.

A mark-and-recapture technique was initiated in 1982 to estimate the total smolt emigration. This technique used the catch efficiency (i.e., proportion of dyed smolts recaptured) of the sampling gear to estimate the proportion of the total migration being sampled (Rawson 1982). That is:

$$\hat{N} = \frac{nD}{d} \quad 1 + \frac{D-d}{Dd}$$

Where: $\hat{N}$ = estimated total population

D = number of fish dyed

d = number of dyed fish recaptured

n = number of unmarked smolt caught in traps

The estimated variance of $\hat{N}$ may be calculated from the formula:

$$\mathrm{Var}\ (\hat{N}) = n\ (n + d)\ D\ (D - d)/d^3.$$

From the estimated variance, a 95% confidence interval for $\hat{N}$ may be determined under the assumption of a normal distribution of N.

A major assumption was that the catch efficiency of each net was a function of changing water levels in the outlet stream, i.e., the higher the water level, the lower our catch efficiency and vice versa. The assumption was also made that the catch efficiency at certain water levels would be constant over time. Another major assumption, later shown invalid, was that marked smolts released into the lake would leave the lake before the dye wore off the fish. This delay in re-emigration from the lake invalidated the attempt to determine the instantaneous trap efficiencies at various water levels. Finally, when two nets were in use, the fish captured were pooled, treating both as one net.

The initial smolt marking procedure used water soluble dyes. As this procedure did not produce recognizable smolts over a minimum time period of five days, a caudal fin punch was substituted as the marking procedure. Fish other than those subsampled for age-weight-length data were used for the mark-and-recapture study. As marking was conducted throughout the smolt emigration period, different clipped fins were used because smolts marked at different times overlapped in subsequent downstream sampling. A large percentage of a total daily catch was marked to enhance the recapture efforts. Fish were taken from the holding-box, anesthetized in MS-222, marked, and upon recovery released into the outlet area of the lake. Once the mark-and-recapture study began, the daily catch was examined for marked smolts with recaptured smolts excluded from the daily total catch.

Adult Enumeration and Sampling

The adult salmon escapement into Falls Lake in 1981 and 1982 was monitored through the use of a picket weir installed in the outlet stream (Figure 1). In addition, a holding-box used to subsample adult fish was incorporated into the weir. Fish were monitored daily for total count, species, sex, and age-weight-length data, and periodically sampled for fecundity. A representative subsample of up to 40 adult sockeye and incidental catches of adult coho were collected each day. If the total daily catch was less than 40 adult sockeye, then 100% of the catch was sampled. To prevent recounting the same fish, all captured adults were released upstream of the weir.

Adults subsampled for species composition, sex, and age-weight-length data were anesthetized in MS-222, weighed to the nearest 0.1 kg, measured (mid-eye to fork length) to the nearest 0.5 cm, and had scales removed from the preferred area. The scales were placed on labeled gum cards and later analyzed by the Stock Separation group of the Commercial Fisheries Division of the ADF&G. Data collection was organized such that specific information could later be referred back to the source fish. All sampled adults were allowed to recover before being released upstream of the weir.

Natural prespawning mortalities, which had been killed in the falls and washed back into the weir, were used for measuring the fecundity. A 100 gram subsample of the total number of eggs in each female was weighed and then the individual eggs in the subsample were hand-counted. The number of eggs per gram of weight was then used to expand the total weight of the eggs into actual fish fecundity.

An estimate of the subsistence catch of Falls Lake sockeye salmon was obtained from subsistence permits issued by the Commercial Fisheries Division in Sitka and Petersburg.

Resident Char Enumeration and Sampling

In 1981, a mark-and-recapture study was conducted using the Schumacher-Eschmyer method to estimate the number of rearing Dolly Varden char in Falls Lake. Minnow traps, baited with salmon eggs enclosed in perforated plastic film cases, were strategically placed along the shoreline and monitored six or seven times a day for several days. The captured Dolly Varden were marked with a small hole in the caudal fin and returned to the Lake. Total catches and number of recaptures were collected daily. A mark-and-recapture estimate was made once each month during July, August, and September.

RESULTS

Native Resident and Anadromous Fish

Six species of fish were found in the Falls Lake system (Table 1) although one (pink salmon) was found only in the outlet stream. The remaining five species inhabit the lake for varying lengths of time and were sampled through the use of tow netting, beach seining or through the use of minnow traps.

Rearing Sockeye Fry

In October of 1981, sockeye fingerlings were sampled for growth and for age composition by tow netting at five depths within the lake (*see* Appendix A). Although the sample size is small (n=14), we caught few fish above 10 m with most of the fish concentrated between 10 and 15 m (Table 2). Age 0.0 fingerlings ranged in size from 37 mm to 51 mm or from 0.42 g to 1.5 g while age 1.0 fingerlings ranged from 60 m to 62 mm or from 2.14 g to 2.29 g. Overall, age 0.0 fingerlings averaged 45 mm in length and 0.87 g in weight compared to a mean size of 61 mm and 2.22 g for the age 1.0 fingerlings. Unfortunately, hydroacoustic gear was not used in conjunction with the mid-water trawl; consequently, the number of rearing fish caught in the tow net was extremely low. Thus, the age composition of 29% age 1.0 fish and 71% age 0.0 fingerlings may only be used to indicate the presence of a significant fraction of age 1.0 fingerlings.

Population Characteristics and Estimated Numbers of Sockeye and Coho Smolts

The timing of sockeye smolt emigration from Falls Lake varied between 1981 and 1982. This variability can be attributed to contrasting winter climatic conditions that occurred during the two years of study. A mild winter was experienced in 1981 with no observed ice cover on Falls Lake. Conversely, in 1982 the winter was colder with lake ice lasting until 29 May. Consequently, the peak emigration in 1981 occurred early during the first three weeks of May, but was delayed in 1982, lasting from 27 May to 10 June.

In 1981, a total of 725 sockeye smolts were captured. Since the daily catch never exceeded the desired subsample number of 40 smolts per day, all of the captured smolts in 1981 were sampled. Overall, the smolts averaged 72.3 mm in length and 2.9 g in weight (Table 3). Age composition was determined by length-frequency analysis (Figure 2) rather than scale analysis, due to the difficulty of obtaining accurate annuli counts from the smolt scales. The separation between age 1.0 and age 2.0 smolts apparently occurred at 75 mm which resulted in approximately 60% of the smolts being designated age 1.0 and 40% being classified as age 2.0. Based on this break-down, age 1.0 smolts averaged 68 mm in length while age 2.0 smolts averaged 82 mm in length. Finally, a total of 36 coho salmon smolts was also captured incidentally to the sockeye smolts. The weights of these smolts ranged from 6.0 g to 18.8 g with a mean of 9.9 g while lengths ranged from 90 mm to 133 mm with a mean of 106.5 mm. The age composition of the coho salmon smolts was 5.7% age 1.0, 91.4% age 2.0, and 2.9% age 3.0 as determined from scale pattern analysis.

Table 1. List of common and scientific names of fish species native to Falls Lake, Baranof Island.

Common name	Scientific name
Sockeye salmon	*Oncorhynchus nerka*
Coho salmon	*Oncorhynchus kisutch*
Dolly Varden	*Salvelinus malma*
Threespine stickleback	*Gasterosteus aculeatus*
Slimy sculpin	*Cottus cognatus*
Pink salmon[1]	*Oncorhynchus gorbuscha*

[1]Found only in the outlet stream.

Table 2. Age-weight-length data of juvenile sockeye salmon collected during tow netting on 8 October 1981 with a mid-water trawl.

Tow Depth	Number caught	Length	Weight	Age
2.5 m	0	--	--	--
5.0 m	0	--	--	--
7.5 m	1.	62 mm	2.296 g	1.0
10.0 m	1.	37 mm	0.416 g	0.0
	2.	38 mm	0.442 g	0.0
	3.	42 mm	0.679 g	0.0
	4.	46 mm	0.987 g	0.0
	5.	50 mm	1.228 g	0.0
	6.	60 mm	2.181 g	1.0
	7.	62 mm	2.258 g	1.0
15.0 m	1.	40 mm	0.566 g	0.0
	2.	55 mm	1.481 g	0.0
15.0 m	1.	43 mm	0.803 g	0.0
	2.	45 mm	0.904 g	0.0
	3.	51 mm	1.234 g	0.0
	4.	60 mm	2.137 g	1.0
	Mean	49.4 mm	1.258 g	
			Age composition	0.0 (71%) 1.0 (29%)

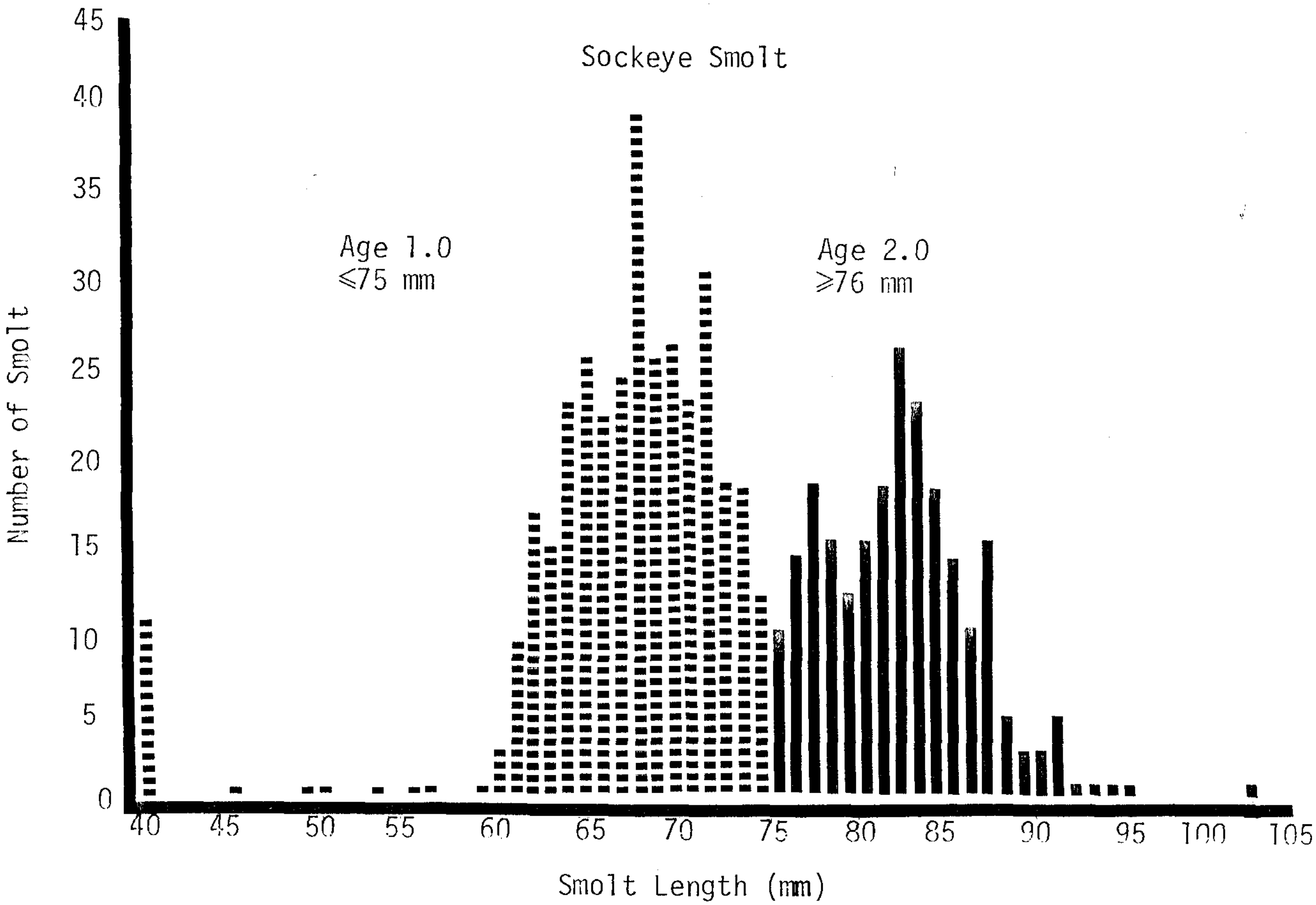


Figure 2. Length-frequency histogram showing the proportion of age 1.0 and age 2.0 sockeye smolts along with the size used to delineate the two age classes.

In 1982, a total of 13,198 sockeye salmon smolts were captured with approximately 10% of the smolts subsampled for age-weight-length data. The mean size of the sockeye salmon smolts was 2.6 g (by weight) and 68.0 mm (by length) (Table 4). In addition, scale pattern analysis on these smolts revealed that 4.0% were age 1.0, 83% were age 2.0, and 13% were age 3.0. Age 1.0 sockeye smolts had a mean length of 67 mm and weighed 2.4 g while age 2.0 smolts averaged 70 mm in length and 2.8 g in weight. Finally, incidental catches of coho salmon smolts totalled 523 in 1982. Subsamples of these smolts revealed a mean size of 13.3 g (by weight) and 114.0 mm (by length) (Table 4). Scale analysis showed that the coho salmon smolts were 1% age 1.0, 81% age 2.0, and 18% age 3.0.

In order to estimate the capture efficiency of the fyke nets for use in estimating smolt numbers, groups of marked sockeye and coho smolts were released five different times from 21 May to 5 June 1982 (Tables 5 and 6, respectively). Unfortunately, the water soluble dyes originally chosen for the study (Kyle and Koenings 1982) did not stain the fish sufficiently for visual identification for a period longer than two or three days. This proved unacceptable since marked fish left the lake up to ten days after release (Table 5). The delay in re-emigration caused by their release back into the slow water above the falls created an overlap between marked groups, and consequently, differential fin clips had to be used to delineate each group of smolts. Fluctuating water levels and a low recapture efficiency further compounded the lack of precision. Because of these problems, we felt that the assumptions used by Rawson (1982) were not valid, and we estimated the relative magnitude of the smolt emigration from Falls Lake in 1982 by using an overall net efficiency of 10.5% for sockeye (Table 5) and 7% for coho (Table 6). This gives an order of magnitude for the 1982 emigration of 125,000 sockeye smolts and 7,000 coho smolts.

One important parameter which must be refined during the spring of 1983 (pre-fertilization phase), is our ability to define the total number and/or biomass of sockeye and coho smolts that Falls Lake is producing. The total quantity of smolts emigrating from Falls Lake was not obtained in the feasibility program of 1981, and a statistically precise estimate was not obtained in 1982 due to a mid-season switch in the smolt marking methodology; however, the netting efficiency calibration that was accomplished did provide the information necessary to calculate a conservative point estimate of smolt numbers. Hopefully, the procedures incorporated into the 1983 smolting program will be successful in providing at least one year of statistically defined smolt production prior to fertilization.

Population Characteristics and Spawning Density of Sockeye and Coho Adults

In 1981, the adult weir was operated from 26 June to 17 September, and in 1982, from 23 June to 27 August. A total of 1,293 adult sockeye were counted through the weir in 1981, and 1,687 fish were counted in 1982 with peak sockeye escapement into Falls Lake occurring in both years from mid-July to mid-August (*see* Appendix B). A portion of the adult coho escapement into Falls Lake was monitored in 1981 (152 fish) and 1982 (137 fish) before the removal of the weir. Additional adult coho salmon may have

Table 3. Weekly catches, mean weights and lengths, and age composition of sockeye salmon smolts emigrating from Falls Lake in 1981.

Weekly period	Weekly catch	Mean weight (g)	Mean length (mm)	Age Composition* 1.0	2.0	3.0
4/20 - 4/26	2	2.8	66.5	--	--	--
4/27 - 5/03	82	3.6	79.9	--	--	--
5/04 - 5/10	190	3.1	75.6	--	--	--
5/11 - 5/17	149	2.8	73.2	--	--	--
5/18 - 5/24	164	2.6	69.3	--	--	--
5/25 - 5/31	97	2.3	69.5	--	--	--
6/01 - 6/07	40	Data not available		--	--	--
6/08 - 6/14	1	Data not available		--	--	--
Total	725	2.9	72.3			

*Age composition was estimated by length frequency and is presented in Figure 2.

Table 4. The weekly catches, mean weights and lengths, and age composition of sockeye and coho salmon smolts emigrating from Falls Lake in 1982.

	Sockeye						Coho					
				Age composition						Age composition		
Weekly period	Weekly catch	Mean weight (g)	Mean length (mm)	1.0	2.0	3.0	Weekly catch	Mean weight (g)	Mean length (mm)	1.0	2.0	3.0
5/04-5/10	--	--	--	--	--	--	1	10.4	105.0	--	--	--
5/11-5/17	46	3.1	72.9	7%	75%	18%	18	9.3	108.0	6%	72%	22%
5/18-5/24	282	3.0	71.3	0%	67%	33%	67	12.9	111.0	0%	74%	26%
5/25-5/31	3,967	2.7	69.0	2%	85%	13%	216	18.0	118.0	0%	89%	11%
6/01-6/07	5,522	2.6	67.8	2%	81%	17%	195	15.6	121.0	0%	85%	15%
6/08-6/14	2,717	2.3	66.4	5%	92%	3%	24	13.7	112.0	--	--	--
6/15-6/21	664	2.5	68.0	7%	88%	5%	2	--	--	--	--	--
Total	13,198	2.6	68.0	4%	83%	13%	523	13.3	114.0	1%	81%	18%
		Mean Length (mm)		67	70	76				99.5	113.4	124.1
		Mean weight (g)		2.4	2.8	3.5				9.6	13.5	17.5
		Number		52	1,079	169				2	102	20

Table 5. Results of the mark-and-recapture of sockeye salmon smolts in Falls Lake, 1982.

Date Marked	Type of Mark	Number Released	Recaptures Date	Recaptures Numbers	Percent Recaptured
5/21	Bismark brown dye	39 sockeye		0	0
5/24	Upper caudal lobe clip	80 sockeye	5/24	1	
			5/26	1	
				2	3%
5/25	Lower caudal lobe clip	56 sockeye	5/26	1	
			5/29	1	
			5/30	2	
				4	7%
5/29	Upper caudal lobe clip + neutral red dye	560 sockeye	5/30	15	
			5/31	3	
			6/1	2	
			6/3	6	
			6/4	2	
			6/5	2	
			6/6	1	
			6/9	2	
			6/11	1	
				34	6.1%
6/5	Lower caudal lobe clip	300 sockeye	6/5	3	
			6/6	9	
			6/7	11	
			6/8	9	
			6/9	9	
			6/10	18	
			6/11	6	
			6/12	1	
			6/13	2	
			6/15	1	
				69	23%
Overall		1035 sockeye		109	10.5%

Table 6. Results of the mark-and-recapture of coho salmon smolts in Falls Lake, 1982.

Date Marked	Type of Mark	Number Released	Recaptures Date	Recaptures Numbers	Percent Recaptured
5/21	Bismark brown dye	9 coho		0	0
5/24	Upper caudal lobe clipped	20 coho	5/26	1	5%
5/25	Lower caudal lobe clipped	23 coho	5/26	1	
			5/27	1	
				2	9%
5/29	Upper caudal lobe clipped and neutral red dye	26 coho	5/30	1	
			6/1	2	
				3	12%
6/5	Lower caudal lobe clipped	30 coho	6/5	1	
			6/7	1	
				2	7%
Overall		108		8	7%

entered the system after the weir was removed at the end of August in 1982, and the middle of September in 1981; however, peak escapements were recorded for both years in the third week of August so additional spawners would be few (*see* Appendix C).

The sex and age composition of the adult sockeye escapement into Falls Lake in 1981 and 1982 was somewhat variable (Table 7). The dominant age class in 1981 was 2.3, which switched to the 1.2 and 2.2 age classes in 1982. In addition, the returning fish in 1981 resulted from a large percentage (57%) of age 2.0 smolts and consisted of a sizeable fraction (57%) of three-ocean adults. In comparison, the 1982 returning fish resulted from slightly fewer age 2.0 smolts (47%) and still fewer three-ocean adults (37%). Further, in both years 4-year-old fish represented approximately one-third of the escapement while in 1981 6-year-old fish dominated the return (47% of the fish), but in 1982 5-year-old fish (50% of the fish) returned in the greatest numbers.

Finally, the sex ratio of males to females was 1.7:1.0 in 1983 and 1.3:1.0 in 1982. The sex and age composition of the portion of the adult coho escapement monitored in 1982 is presented in Table 8. The dominant age class for the adult coho salmon was 2.1 with the sex ratio of males to females being 1.4:1.0.

In 1981, adult female sockeye returning to Falls Lake averaged 53.2 cm in length and 1.9 kg in weight, while adult male sockeye averaged 55.9 cm in length and 2.4 kg in weight. For comparison, the 1982 adult females averaged 52.4 cm in length and 1.8 kg in weight, while the adult males averaged 54.4 cm in length and 2.2 kg in weight. Fecundity counts obtained from 33 sockeye, having an average weight of 1.9 kg and an average length of 54.4 cm, averaged 2,480 eggs per female. Size data were also collected on adult coho returning to Falls Lake in 1982, but not in 1981. The adult female coho salmon averaged 59.6 cm in length and 2.7 kg in weight, while the adult male coho salmon averaged 59.7 cm in length and 3.0 kg in weight.

Records of the subsistence catch from Falls Lake were compared to the catch recorded on the subsistence permits issued for Falls Lake (Table 9). The estimated subsistence catch ranged from 654 fish in 1981 to 314 fish in 1982, but was as high as 877 fish as recently as 1980. However, these figures may be in error due to fish from a neighboring sockeye salmon system at Gut Bay being included in the total, so the fish attributed to Falls Lake should be used to indicate only the relative magnitude of the actual subsistence catch.

Population Estimates of Resident Char

In September of 1981, the Dolly Varden population in Falls Lake was estimated to be between 1,154 and 1,518 fish (95% confidence interval, P=.05). The Dolly Varden caught in Falls Lake ranged in size from 68 mm to 485 mm, with a mean length of 135.5 mm. Large schools of Dolly Varden were not observed near sockeye spawning redds nor were they readily caught by sport fishing. Finally, incidental catches of rearing coho juveniles and sticklebacks were made at Falls Lake while sampling for Dolly Varden char; however, a

Table 7. Sex and age composition of adult sockeye salmon sampled from Falls Lake weir in 1981 and 1982.

1981*

Age Class

	1.2		2.2		1.3		2.3		3.3		2.4		Total	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Males	120	14.4	36	4.3	40	4.8	312	37.5	17	2.0	0	0.0	525	63.0
Females	150	18.0	50	6.0	18	2.2	82	9.8	8	1.0	0	0.0	308	37.0
Total	270	32.4	86	10.3	58	7.0	394	47.3	25	3.0	0	0.0	833	100.0

1982

Age Class

	1.2		2.2		1.3		2.3		3.3		2.4		Total	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Males	84	28.2	65	21.8	84	28.2	64	21.5	0	0.0	1	0.3	298	56.0
Females	89	38.0	96	41.0	21	9.0	27	11.5	1	0.4	0	0.0	234	44.0
Total	173	32.5	161	30.3	105	19.7	91	17.1	0	0.2	1	0.2	532	100.0

* Includes only fish passed through the weir prior to August 13. An additional 183 fish were counted from August 14 to September 2.

Table 8. Sex and age composition of adult coho salmon from Falls Lake in 1982.

	Age Class							
	1.1		2.1		3.1		Total	
	No.	%	No.	%	No.	%	No.	%
Males	17	20.7	27	32.9	4	4.9	48	58.5
Females	12	14.7	22	26.8	0	0.0	34	41.5
Total	29	35.4	49	59.7	4	4.9	82	100.0

Table 9. Historical subsistence records for Falls Lake, Baranof Island.

Year	Number of Permits Issued	Number of Sockeye Caught
2/		
1975	3	11
1976	14	294
1977	22	192
1978	Unknown 1/	---
1979	43	369
1980	40	877
1981	34	654
1982	31	314

1/ Data was collated with Gut Bay catch and consequently no specific data for Falls Lake are available.

2/ Prior to 1975 the subsistence records for Falls Lake were combined with that of Gut Bay and Redbluff Bay.

population estimate was not made for either the juvenile coho or sticklebacks (*see* Appendix D).

DISCUSSION

In order for lake enrichment to result in the enhancement of sockeye production from Falls Lake, the rearing environment must be limiting smolt production. If so, the population characteristics of the smolt and adult fish should reflect a poor rearing environment. That is, if the production of smolt is limited by either a small spawning area or simply by a short term reduction in the numbers of spawning fish (escapement limited), lake enrichment will not likely result in a recognizable increase in smolt production. However, both these latter two conditions should be mirrored in the population characteristics of the smolt and returning adults. Thus, the central question to be addressed is the balance that exists within the lake between the quality and quantity of forage items (principally zooplankton) and the number of foraging fry. This balance subsequently determines both the quality and quantity of sockeye smolts, and the ocean age of adult fish.

In general, if the rearing fry:forage capacity ratio is small, the rearing capacity is not being challenged, i.e., the lake is spawning area limited. In this case, the zooplankton population should reflect a minimum predation pressure; and, the rearing fry should mature to the smolt phase after one year of freshwater residence (>85%), and be larger than 60-65 mm (>2 g). If the rearing fry:forage capacity ratio has shifted so that the rearing area is being negatively impacted by numerous rearing fry, then the zooplankton population should reflect the heavy foraging pressure. In this case, the resulting smolts should either be all (∿85%) age 1.0 smolts of a minimum size (60-65 mm or ∿2 g) or a sizeable (>50%) population should rear for more than 1 year in freshwater, and the resultant smolts should be larger than 60-65 mm (>2 g).

Similarly, the population characteristics of the adult fish should reflect either a surplus rearing area (spawning area limited) or an inferior rearing area (rearing area limited). In general, larger age 1.0 smolts produce a majority of four-year-old adults with two years of ocean residence. As the rearing area becomes inferior and/or is overtaxed by the rearing fry, the resultant smolts first undergo a decrease in size, which results in five and six-year-old adult fish beginning to dominate the population with three to four years of ocean residence becoming increasingly common. Thus, by following the population characteristics of both the adults and smolts, we can define the quality of freshwater rearing, i.e., the balance existing between the number of rearing fry; and the rearing potential or carrying capacity of the lake.

The 1,293 sockeye returning to Falls Lake in 1981 were found to consist of three-ocean (57%) and two-ocean (43%) fish with a majority of the adults six-years-old (47%). For a similar sized escapement in 1982 (1,687 fish), three-ocean fish represented only 37% of the return while two-ocean fish made up nearly two-thirds (63%) of the escapement. In 1982, unlike the 1981 escapement, five-year-old adults dominated the returning run. Thus, we observed that in both years a sizeable proportion of the escapement consisted of five and six-year-old fish. Additionally, we found that 57% of the 1981 adults returning to Falls Lake consisted of fish that spent two years rearing in the lake before smolting with an additional 3% spending three years rearing to the smolt stage. The remaining 39% of the fish had spent one year rearing in the lake before smolting. In 1982, this pattern shifted slightly so that 47% of the returning fish had spent two years rearing in the lake while 53% had spent only one year rearing before smolting. Whereas the two-year freshwater fish may have a marine survival advantage over one-year smolts (because of a potential larger size), we believe that the returning adults of both years consisted of a sizeable fraction that had spent two years or more rearing in the lake before smolting. This pattern is certainly consistent with the population characteristics found in the 1981 and in 1982 Falls Lake smolts. Moreover, the adult fish which had the greatest proportion of extended rearing in freshwater (1981) also had the greatest percentage of three-ocean fish and the highest percentage of six-year-old adults. Thus, those fish (1982) which had a high percentage (53%) of one year freshwater rearing also had a sizeable percentage of two-ocean fish and the highest percentage of five-year-old-adults. Although within brood-year information is incomplete, the within year information obtained from the adult fish in both 1981 and in 1982 is consistent with Falls Lake being characterized as rearing area limited.

In the spring of 1981, we found that the smolt population contained a sizeable fraction (40% of the outmigration) of age 2.0 fish. In addition, the average length of the age 1.0 smolts was 68 mm with an overall smolt size of 72 mm and 2.9 g. In 1982, we estimated that 125,000 smolts emigrated from the lake, and that 96% of the smolts had reared for two or three years. In addition to the extended rearing, the smolts were again small, with age 1.0 smolts averaging 67 mm (2.4 g) and age 2.0 smolts averaging only 70 mm (2.8 g). Like the extended freshwater residence time found for the 1981 and 1982 adult fish, a significant portion of the smolts emigrating in both 1981 and 1982 had reared for more than one year, and were also of a small size. Both conditions are consistent with the rearing area in Falls Lake limiting the quality and quantity of sockeye smolts. That is, we feel that the quality of the smolts is reduced because of their consistently small size, and further that the quantity is reduced because of the increased predation that may take place on these smaller rearing fry during an extended freshwater rearing period.

Finally, the mean size of the sockeye smolt population emigrating from Falls Lake is small especially when compared to sockeye smolt populations from clear water Cook Inlet and Bristol Bay area lakes (Table 10). However, the size of smolts are comparable to smolts produced in southeast Alaska from McDonald and Hugh Smith Lakes near Ketchikan (Haddix and Peltz 1982), and the glacial lakes in Cook Inlet. It should be noted that the smolts emigrating from both McDonald and Hugh Smith Lakes are predominantly age 1.0 with a small proportion of age 2.0 smolts, but Falls Lake tends to produce a larger percentage of age 2.0 smolts with an additional component of age 3.0 smolts.

Table 10. Mean weights and lengths of sockeye smolts from different systems in Alaska compared to 1982 mean weights and lengths of sockeye smolts from Falls Lake.

Location	Mean Length (mm) Age 1	2	3	Mean Weight (g) Age 1	2	3
Clear water lakes						
Hidden Lake	143	200		27.3	83.9	
Big Lake	132	166		25.5	48.1	
Naknek Lake	100	113		9.2	12.6	
Kvichak Lake	89	110		6.1	10.1	
Togiak Lake	85	101		5.5	9.5	
Red Lake	85	111		5.8	12.8	
Russian River	84	93		5.1	6.5	
Brooks Lake	83	109		5.2	10.1	
Desire Lake	74	92		4.7	8.8	
Delight Lake	71	81		3.6	5.4	
Falls Lake	67	70	76	2.4	2.8	3.5
Glacial lakes						
Tustumena Lake	68	85		2.7	4.8	
Crescent Lake	68	76		2.8	3.8	
Kenai Lake	62	72		2.1	3.1	

Falls Lake also serves as a rearing area for coho salmon. In 1982, 7,000 coho smolts were estimated to leave the lake after rearing for two to three years. In fact, age 1.0 coho smolts equalled 6% of those sampled in 1981, and only 1% of the total coho smolts sampled in 1982. In addition, the number of spawning adults was fairly low in both years the weir was operated. In 1981, 152 coho were passed through the adult weir compared to 137 fish in 1982. Thus, compared to the density of sockeye salmon adults and smolts, the population of coho salmon is considerably lower. However, considering the limited littoral area, which is restricted to a small area in the southwest corner of the lake, the low numbers of coho smolts being produced by the system are not surprising. Coho fry feed, to a large extent, on benthic invertebrates found within the littoral zone, yet zooplankton have been shown to be a sizeable portion of rearing coho forage especially when the fry are added to fish-less lakes (Crone 1981). However, lakes containing a sizeable population of rearing sockeye fry, normally contain zooplankters which are of a smaller size due to the size selective nature of sockeye predation. This downward size shift to below 1.0 mm within the zooplankton community severely restricts the use of zooplankton as a food source by rearing coho since preferred prey items are $\geq$1.0 mm in size. Consequently, rearing coho are often forced to the littoral zone to feed on benthic invertebrates and wind blown terrestrial insects.

In conclusion, Falls Lake is located in a steep-sided basin that limits the amount of direct sunlight the lake receives on both a daily and annual basis. Without this exposure, annual productivity levels may be delayed due to the limited available light reducing the length of the growing season. Nutrient enrichment of this lake during the peak growing period should greatly enhance the growth and survival of the rearing salmonids. This should result both in an increase in the marine survival of the larger smolts and the subsequent adult return which, in turn, would supplement the traditional fisheries supported by Falls Lake and neighboring anadromous systems. The increase in tertiary production would be particularly notable if the enhancement program increased both the number and size of age 1.0 sockeye smolts.

ACKNOWLEDGEMENTS

The pre-fertilization study on Falls Lake was accomplished through a cooperative project agreement between the FRED Division of the Alaska Department of Fish and Game, the United States Forest Service, and the Northern Southeast Regional Aquaculture Association. Without the commitment of time, equipment, and money from these agencies this study would not have been accomplished.

We would like to especially thank the field crews that were responsible for the operation of the weirs, and the personnel from the Commercial Fisheries Division of the Alaska Department of Fish and Game (Stock Biology Group and Southeast Research) that analyzed adult sockeye and coho scales. We also wish to thank Mike Haddix and Gary Kyle for editing the report.

REFERENCES

Crone, R. A. 1981. Potential for production of coho salmon (*Oncorhynchus kitsutch*) in lakes with outlet barrier falls, Southeastern Alaska. Dissertation. University of Michigan, Ann Arbor, Michigan, U.S.A.

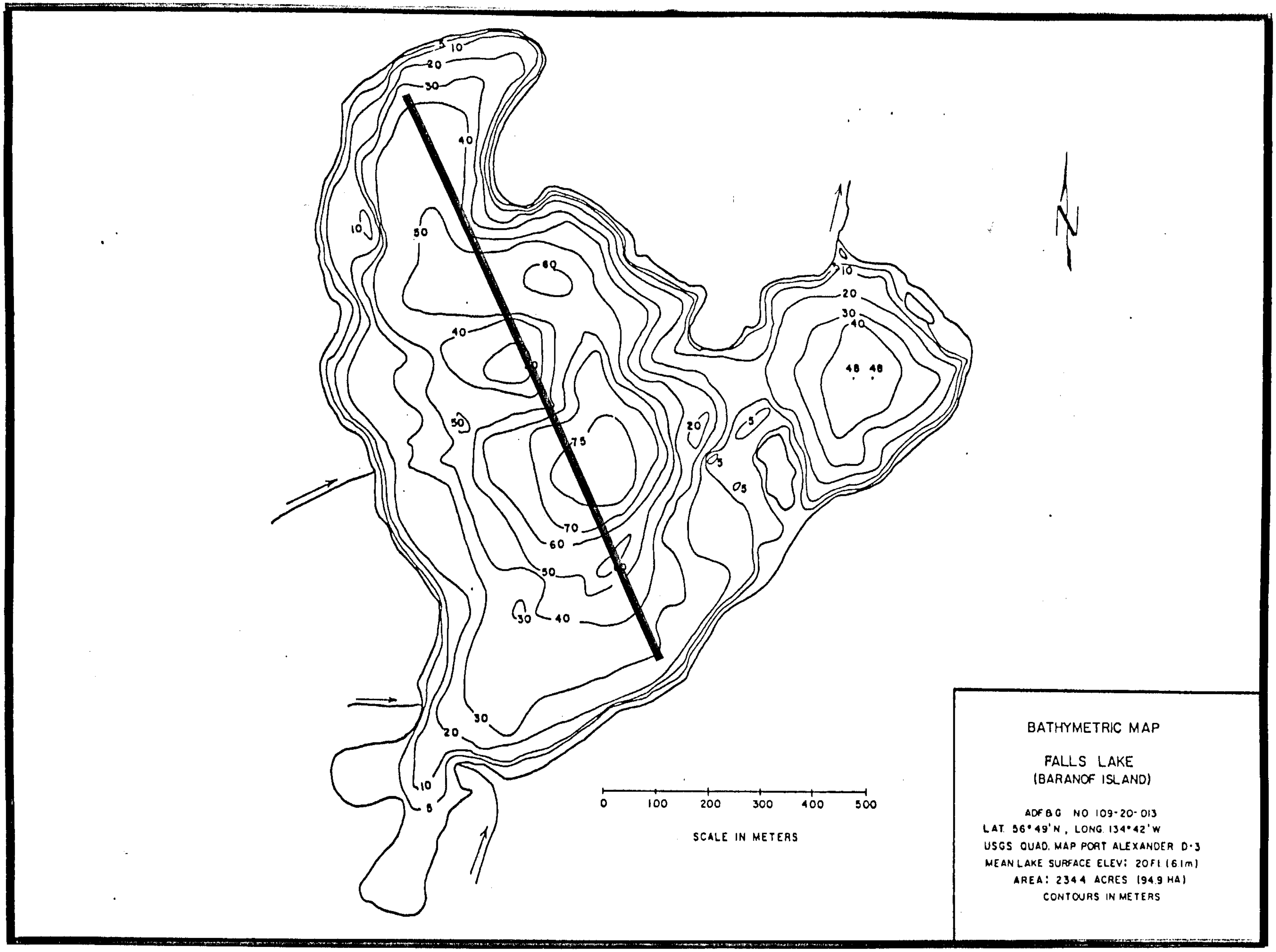
Gjernes, T. 1979. A portable mid-water trawling system for use in remote lakes. Department of Fisheries and Oceans, Resource Services Branch. Pacific Biological Station, Nanaimo, B. C. Technical Report Series. 10 p.

Haddix, M. and L. Peltz. 1982. McDonald Lake Fisheries Data Summary, 1981. Alaska Department of Fish and Game. Unpublished report. 24 p.

Kyle, G. B. and J. P. Koenings. 1982. Crescent Lake sockeye salmon smolt enumeration and sampling, 1981. Alaska Department of Fish and Game. Unpublished Annual Report. 27 p.

Moser, Kenneth H. 1968. Photographic atlas of sockeye salmon scales. Fisheries Bulletin 67(2):243-280.

Rawson, K. 1982. Statistical analysis of dye marking studies. Alaska Department of Fish and Game. Unpublished report. 9 p.



Appendix A. Location of the mid-water trawl transect (▬) used to collect rearing fry at Falls Lake on 8 October 1981.

Appendix B. Daily counts of the adult sockeye salmon passed through the weir at Falls Lake in 1981 and 1982.

Date	1981 Passed daily	1981 Cumulative total	1982 Passed daily	1982 Cumulative total
6/29	60	60	--	--
6/30	24	84	1	1
7/01	13	97	1	2
7/02	2	99	--	2
7/03	11	110	--	2
7/04	3	113	1	3
7/05	9	122	18	21
7/06	3	125	3	24
7/07	--	125	1	25
7/08	--	125	2	27
7/09	--	125	--	27
7/10	--	125	--	27
7/11	--	125	--	27
7/12	2	127	--	27
7/13	4	131	--	27
7/14	5	136	1	28
7/15	21	157	--	28
7/16	31	188	--	28
7/17	52	240	2	30
7/18	31	271	9	39
7/19	20	291	6	45
7/20	8	299	1	46
7/21	14	313	18	64
7/22	22	335	78	142
7/23	14	349	106	248
7/24	19	368	274	522
7/25	20	388	432	954
7/26	31	419	92	1,046
7/27	32	451	187	1,233
7/28	33	484	96	1,329
7/29	26	510	90	1,419
7/30	19	529	63	1,482
7/31	20	549	19	1,501
8/01	33	582	38	1,539
8/02	32	614	26	1,565
8/03	30	644	14	1,579
8/04	37	681	7	1,586
8/05	85	766	12	1,598
8/06	148	914	8	1,606
8/07	51	965	2	1,608
8/08	19	984	12	1,620
8/09	27	1,011	5	1,625
8/10	31	1,042	--	1,625
8/11	32	1,074	--	1,625
8/12	31	1,105	--	1,625
8/13	5	1,110	7	1,632
8/14	7	1,117	--	1,632
8/15	8	1,125	18	1,650
8/16	8	1,133	2	1,652
8/17	25	1,158	2	1,654
8/18	27	1,185	9	1,663
8/19	45	1,230	0	1,663
8/20	22	1,252	1	1,664
8/21	1	1,253	3	1,667
8/22	7	1,260	6	1,673
8/23	4	1,264	4	1,677
8/24	5	1,269	3	1,680
8/25	4	1,273	2	1,682
8/26	5	1,278	3	1,685
8/27	3	1,281	2	1,687
8/28	3	1,284	Weir Removed	
8/29	2	1,286		
8/30	--	1,286		
8/31	2	1,288		
9/01	4	1,292		
9/02	1	1,293		

Appendix C. Daily counts of the adult coho salmon passed through the weir at Falls Lake in 1981 and 1982.

Date	1981 Passed daily	1981 Cumulative total	1982 Passed daily	1982 Cumulative total
7/22	--	--	1	1
8/03	--	--	2	3
8/04	1	1	--	3
8/05	2	3	--	3
8/06	3	6	1	4
8/07	2	8	1	5
8/08	--	8	3	8
8/09	--	8	5	13
8/10	--	8	--	13
8/11	--	8	--	13
8/12	--	8	--	13
8/13	--	8	--	13
8/14	--	8	--	13
8/15	--	8	--	13
8/16	--	8	1	14
8/17	--	8	--	14
8/18	--	8	2	16
8/19	4	12	1	17
8/20	12	24	--	17
8/21	13	37	2	19
8/22	28	65	10	29
8/23	10	75	12	41
8/24	1	76	56	97
8/25	4	80	26	123
8/26	3	83	9	132
8/27	--	83	5	137
8/28	--	83	Weir Removed	
8/29	3	86		
8/30	--	86		
8/31	2	88		
9/01-9/17	64	152		

Appendix D. Incidental catches of coho juveniles and stickleback (Stk.) taken from minnow traps at Falls Lake in 1981.

Date	Hours Fished	Catch Coho	Catch Stk.		CPUE* Coho	CPUE* Stk.
7/8/81	3.3	96	196		2.9	5.9
7/9	6.7	30	180		.45	2.7
7/10	17.2	70	210		.41	1.4
7/10	9.8	101	323		1.03	3.3
7/11	8.0	30	127		.38	1.6
7/11	13.5	66	201		.49	1.5
7/12	15.8	70	346		.44	2.2
7/13	11.3	106	296		.94	2.6
7/14	14.2	48	330		.34	2.3
7/24	12.4	137	425		1.10	3.4
7/25	13.5	86	305		.64	2.3
7/26	12.6	46	118		.37	.94
7/27	12.7	76	232		.60	1.8
7/28	13.0	171	244		1.32	1.9
7/29	13.0	71	60		.55	.46
8/24	15.7	12	3		.08	.02
8/25	15.0	71	23		.47	.15
8/28	14.7	238	21		1.62	.14
8/29	14.2	164	16		1.15	.11
8/30	8.2	333	18		4.06	.22
8/31	16.0	230	10		1.44	.06
9/1	15.2	124	12		.82	.08
				$\overline{X}$	.93	1.34
				s	.84	1.14
				range	(.08-4.06)	(.02-3.4)
				n	22	22

*catch-per-unit-effort (fish/trap-hour)

PART II: The Falls Lake Limnology Program

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ABSTRACT

Falls Lake, Northern Southeast Alaska, was studied intensively for two years as a cooperative project between the Alaska Department of Fish and Game, and the U. S. Forest Service. The purpose of the study was to determine the suitability of the lake for inclusion into the lake enrichment program, a sockeye salmon enhancement technique.

Falls Lake is an oligotrophic system currently at 30% of the critical or allowable phosphorus loading level. During the summer period, inorganic nitrogen levels within the epilimnion undergo a severe depression which is accompanied by a moderate depression in reactive silicon. In addition, seasonally defined chlorophyll a levels are very low (≤0.40 ppb) with the zooplankton community being dominated (70%-90%) by extremely small body-sized (≤0.40 mm) herbivorous zooplankters. As such, the existing zooplankton community reflects an intense grazing pressure from rearing fish including sockeye fry. In turn, the sockeye migrate from the lake as small sized smolts after an extended freshwater rearing period of up to three years.

After detailed limnological and fishery study (*see* Part I of this report), it was determined that the quality and quantity of the rearing area in Falls Lake limits current sockeye smolt production. That is, smolt production could be enhanced by the application of inorganic fertilizer to the lake during the summer period. This would act to increase the rearing capacity of the lake for sockeye fry without causing a detrimental change in water quality.

INTRODUCTION

Combined limnological and fisheries investigations on Falls Lake began in 1980 with a feasibility study designed to prioritize lake systems in Northern Southeast Alaska (Koenings and Barto 1981) as to their relative potential for inclusion into the lake enrichment program. Following the selection of Falls Lake as a high priority system, a detailed two year pre-fertilization study began in the spring of 1981 which will be completed in the spring of 1983. At that time, Falls Lake will be a candidate for the actual addition of inorganic fertilizer.

By using this integrated approach to study the ecology of rearing fry, we have questioned the continuing utility of the traditional fisheries paradigm that the reproduction, survival and production of any fish population is virtually independent of changes in abundance of other biotic or abiotic components of the water body. That is, that the system in need of study is comprised solely of a fish population and fishermen. Thus, we feel that the successful application of the fisheries enhancement techniques of lake enrichment (or lake stocking) will only result when the effects of physical and chemical variables, and of other groups of organisms (e.g., zooplankton) within the water body are understood. The single most powerful tool available to gain this functional understanding of fish production is the experimental manipulation of entire lake ecosystems. Thus, the techniques of lake enrichment and lake stocking are used not only to produce additional fish, but are the best tools available to decipher, by observing cause-and-effect relationships, the interacting varibles in freshwater lakes which lead to successful fish production.

This portion of the report serves to summarize the nutrient levels, and the primary and secondary production cycles found in the lake during the pre-enrichment phase. Like the fisheries information, the limnological evaluation will define the 'before' condition to which conditions 'after' the addition of fertilizer will be compared.

Study Site Description

Falls Lake (ADF&G No. 109-20-013) is located on the east side of Baranof Island (lat. 56° 49'N, Long. 134° 42'W) (Figure 1). The lake has a surface area of $0.947 \times 10^{+6}$ m^2 (234 acres), a volume of $30.4 \times 10^{+6}$ m^3 and lies at an elevation of 6 m above sea level. The bottom contours of this system are fairly convoluted, but two major basins lie at the middle and northeast portions of the lake. The maximum depth of the lake (77.5 m) lies in the center basin while the northeast basin shallows to <50 m. The littoral zone is not extensive as the lake basin drops quickly along the margins to depths greater than 20 m. The overall mean depth of the lake is 32 m. A major shallow zone (i.e., ≤15 m) lies on the southwest side of the basin where large beds of aquatic macrophytes were observed during the summer period. The mean annual precipitation at Falls Lake equals 432 cm which falls on a combined lake plus watershed area of 16.6 km^2. Thus, the lake receives a volume of water equal to $57.3 \times 10^{+6}$ m^3 per year which results in a water residence time of approximately 0.53 years.

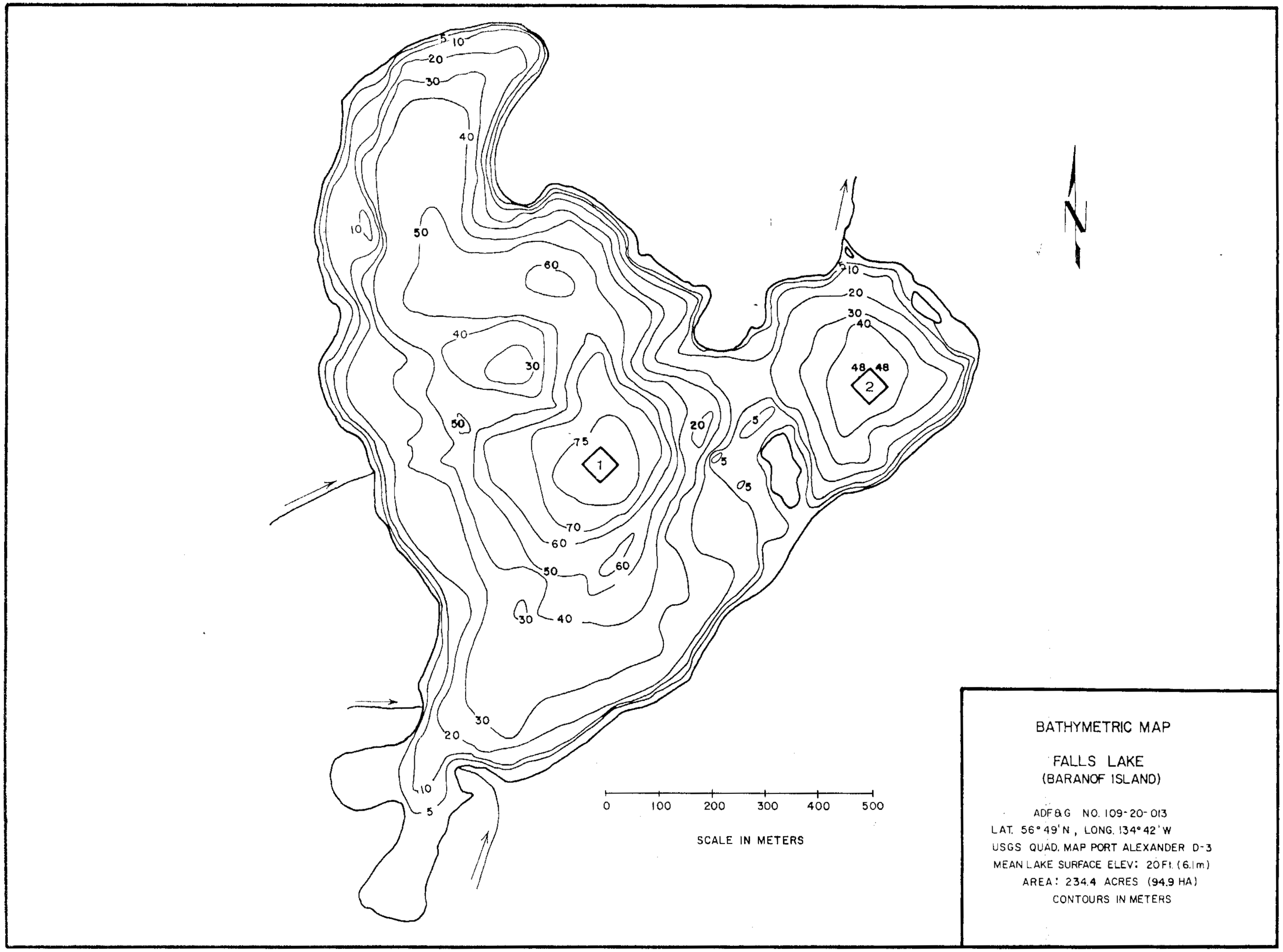

Figure 1. Morphometric map of Falls Lake showing the location of the major basins and the limnological sampling Stations 1 and 2.

METHODS

Transportation to and from both lakes was provided by float-equipped aircraft. Limnological samples were collected by a small boat moored to permanent sampling stations during all surveys. The frequency of sampling was designed to characterize the lake at three-week intervals from ice-off in the spring to ice-on in the winter. The lake was sampled for algal nutrients (nitrogen, phosphorus, silicon and carbon) as well as other water quality parameters (*see* Alaska Department of Fish and Game, Lake Fertilization Guidelines) from both the epilimnetic and mid-hypolimnetic zones. Water samples from multiple (4) casts with a non-metalic Van Dorn sampler were pooled, stored in 8-10 liter transluscent carboys, cooled, and immediately transported in light-proof containers to Sitka for filtering and preservation. Subsequent filtered and unfiltered water samples were stored either refrigerated or frozen in acid cleaned pre-rinsed polybottles. The pre-processed water samples were then sent to the Soldotna Limnology laboratory for analysis.

All chemical and biological samples were analyzed by methods detailed in the Alaska Department of Fish and Game limnology manual (Koenings et al. 1980). In general, filterable reactive phosphorus (FRP) was analyzed by the molybdate blue-ascorbic acid method of Murphy and Riley (1962) as modified by Eisenreich et al. (1975). Total phosphorus was determined by the FRP procedure after persulfate digestion. Nitrate and nitrite were determined as nitrite, following Stainton et al. (1977), after cadmium reduction of nitrate. Ammonium analysis followed Stainton et al. (1977) using the phenolhypochlorite methodology while silica analysis followed the procedure of Strickland and Parsons (1972). Alkalinity levels were determined by acid titration (0.02 N H_2SO_4) to pH 4.5 using a Corning model 399A specific ion meter.

Particulate carbon, nitrogen, and phosphorus were estimated directly from filtered seston prepared by drawing 1 to 2 liters of lake water through pre-cleaned 4.2 cm GF/F filters. The filters were stored frozen in individually marked plexislides until analyzed.

Primary production (algal standing crop) was estimated by chlorophyll a (chl a) analysis after the fluorometric procedure of Strickland and Parsons (1972). We used the low strength acid addition recommended by Reimann (1978) to estimate phaeophytin. Water samples (1-2 liters) were filtered through 4.25 cm Whatman GF/F filters to which 1-2 mls of a saturated $MgCO_3$ solution were added just prior to the completion of filtration. The filters were then stored frozen in plexislides for later analysis.

Zooplankton were collected from either duplicate bottom to surface or 50 m to surface vertical tows using a 0.5 m diameter, 153 μ mesh conical zooplankton net. The net was pulled at a constant 1 m/second, and washed well before removing and preserving the organisms in 10% neutralized sugar-formalin (Haney and Hall 1973).

Identification within the genus *Daphnia* followed Brooks (1957); of the genus *Bosmina* after Pennak (1978); and of the copepods after Wilson and Yeatman (1959), and Harding and Smith (1974). Enumeration consisted of counting triplicate 1 ml subsamples taken with a Hensen-Stempel pipette in a 1 ml Sedgewick-Rafter cell. Size (length) of the individual zooplankters was obtained by counting at least ten individuals along a transect in each of the 1 ml subsamples used in identification and enumeration. Zooplankters were measured to the nearest 0.01 mm as described in Edmondson and Winberg (1971).

Bottom profiles were recorded with a fathometer along several lake transects and from these depth recordings bathymetric maps were developed. Using each map, the area of component depth strata was determined with a polar planimeter, and lake volume (V) was computed by summation of successive strata after Hutchinson (1957):

$$\text{Lake Volume} = \sum_{i=1}^{n} \frac{h}{3} (A_1 + A_2 + \sqrt{A_1 A_2})$$

Where: $\sum_{i-1}^{n}$ = sum of strata volumes i through n.

A_1 = surface area of upper depth strata (m^2)

A_2 = surface area of lower depth strata (m^2)

h = distance between A_1 and A_2 (m)

Lake mean depth ($\bar{z}$) were calculated as:

$$\bar{z} = V/AL$$

Where: $\bar{z}$ = lake mean depth (m)

V = lake volume ($\cdot 10^6 m^3$)

A_L = lake surface area ($\cdot 10^6 m^2$)

The theoretical water residence time (T_w) was calculated as:

$$T_w\ (yr) = V/TLO$$

Where: T_w = theoretical water residence time (years)

V = total lake volume ($\cdot 10^6 m^3$)

TLO = total lake outflow ($\cdot 10^6 m^3 yr$)

The collection of physical data included the measurement of lake temperatures and light penetration at both Stations 1 and 2. Lake temperature profiles were measured using a Hydrolab meter. These recordings were taken at 1 m increments from the surface to 5 m, at 2 m increments from 6-12 m, and at 10 m increments from 20-50 m. The algal light compensation point was defined as the depth at which 1% of the subsurface light [photosynthetically available radiation (400-700 nm)] penetrated, and was measured using a Protomatic submersible photometer. Recordings were taken at several depths between the surface and the compensation depth. Using these data, the natural logarithm of light intensity was plotted against depth, and the slope of this line was used to calculate the light extinction coefficient by date. In addition, water transparency was estimated using a 20 cm Secchi disk.

Finally, in both the Tables and Figures we have used the designation of either mg L^{-1} or μg L^{-1} to report concentration data. However, in the body of the report we have used either parts per million (ppm) in lieu of mg L^{-1} and parts per billion (ppb) in lieu of μg L^{-1}. We have made this conversion in order to reduce the handling time of the report by our support staff.

RESULTS

Physical Features

The euphotic zone of Falls Lake varied considerably during 1981 ranging from 3.51 to 14.15 meters (Table 1). Generally, water clarity tended to change equally at both stations during the open water period, and averaged 8.11 meters at Station 1 and 7.68 m at Station 2. Overall, the euphotic zone of Falls Lake averaged 7.9 m in depth. In addition, there was a general trend for the euphotic zone to decrease in depth from 10 m to 14 m in the spring to 4 m to 5 m by late fall. Corresponding with this decrease was a similar change in the Secchi disk depth which decreased from 5 m to 7 m during the spring to 1 m by late fall. Overall, the Secchi disk depth averaged 3.4 m or 43% of the overall depth of the euphotic zone.

In contrast, during 1982, the depth of the euphotic zone remained fairly uniform increasing from approximately 9 m during the spring to over 14 m by the end of August (Table 1). Thereafter, the euphotic zone began to shallow, but only to a depth of 8 m. Overall, the euphotic zone averaged nearly 11 m in depth. Correspondingly, the Secchi disk depth remained relatively stable varying from 4.0 to 7.0 m and averaged 5.6 m during the ice-free period. Overall, the Secchi disk depth represented 52% of the depth of the euphotic zone.

A second feature of considerable importance to the lake in terms of nutrient utilization is the depth of the epilimnion or the volume of the trophogenic zone during the summer period. In 1981, the lake was isothermal at slightly less than 4°C during April (Figure 2a), warmed slightly at the surface to nearly 9°C by mid-May, and by the first part of June had developed a stable thermal structure. This defined the depth (approximately 10 m) to which wind generated mixing would circulate the water within the epilimnion. Epilimnetic heating continued into the middle of July when temperatures at the surface approached 16°C. Thereafter, the upper surface water temperature remained at or less than 16°C, but the deeper portions of the epilimnion continued to warm through the end of August. In September, the

Table 1. The penetration of phytosynthetically available radiation (PAR) which defines the limit of the euphotic zone (the penetration of 1% of sub-surface light) compared to the depth at which the Secchi disk is no longer visible in Falls Lake for 1981 and 1982 at Stations 1 and 2.

Station / Date	Euphotic zone (m) 1	Euphotic zone (m) 2	Vertical Extinction Coefficient (m-1) 1	Vertical Extinction Coefficient (m-1) 2	Secchi Disk depth (m) 1	Secchi Disk depth (m) 2
1981						
04/21	7.80	7.68	0.61	0.59	5.5	5.0
05/14	10.54	10.28	0.43	0.44	6.5	7.0
06/04	9.86	10.00	0.46	0.43	4.5	4.4
06/24	14.15	12.31	0.32	0.38	6.0	5.0
07/12	10.36	9.31	0.45	0.47	4.5	5.0
08/12	8.48	7.82	0.54	0.59	2.0	2.5
08/26	6.84	7.95	0.64	0.60	3.4	3.0
09/16	6.23	4.68	0.70	0.95	1.1	1.3
09/28	5.08	4.95	0.89	0.89	1.3	1.3
10/30	6.37	5.75	0.70	0.77	2.0	2.0
11/17	3.51	3.74	1.36	1.26	1.0	1.0
1982						
05/01	Ice-cover					
06/09	9.06	8.83	0.49	0.52	6.75	6.25
06/30	11.54	11.99	0.39	0.38	5.25	5.10
07/23	10.26	9.93	0.45	0.46	5.0	5.0
08/12	11.91	11.91	0.39	0.39	6.5	6.75
08/31	13.18	15.36	0.36	0.29	7.0	6.75
09/24	10.87	12.16	0.41	0.37	6.0	5.25
10/13	7.69*	7.69*	--	--	4.00	4.00
11/05	8.02	7.77	0.55	0.57	4.75	4.00
11/30	9.37	9.25	0.49	0.49	6.75	6.00

*Estimated from the relationship S.D./1% light level = 0.52

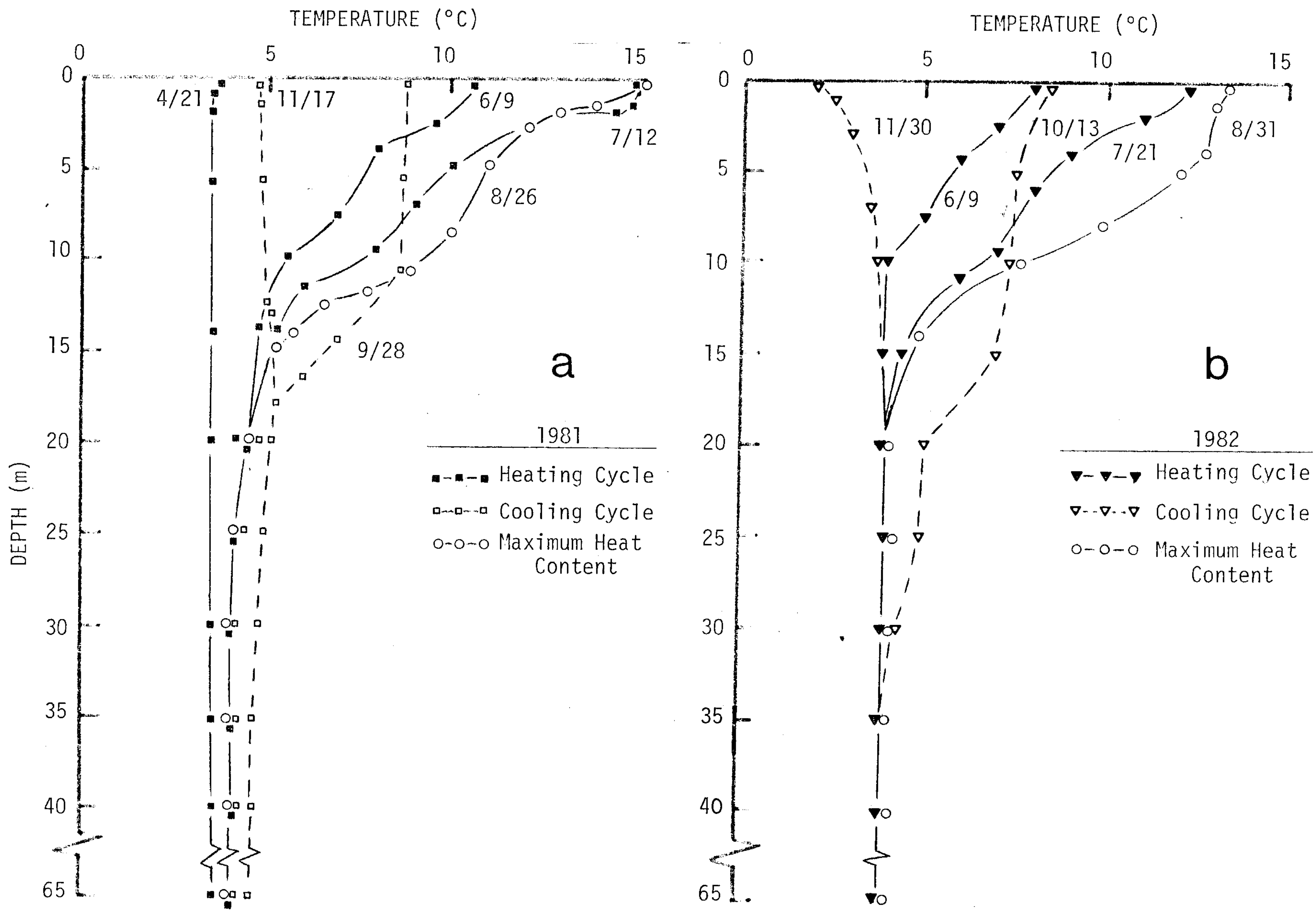

Figure 2. Temperature profiles for Falls Lake at Station 1 for both 1981 (a) and 1982 (b) showing seasonal heating and cooling cycles which define the onset and loss of a stable epilimnion.

lake began to cool both by heat loss to the increasingly cooler air and by deep mixing with cooler water until the end of September. By the middle of November the lake was again isothermal, and mixing from top to bottom. Thus, by wind generated mixing the thermocline or bottom of the epilimnion deepened from 10 m to nearly 16 m from early June to the end of September.

During 1982, the seasonal temperature profiles were much the same as those found in 1981 (Figure 2b). That is, the period of heating lasted from early June to the end of August, but by mid-October the thermal structure had considerably weakened. By the end of November, edge-ice was beginning to form and mid-lake surface temperatures dipped to less than 2°C. Thus, the period of thermal stability lasted from the first part of June to the first part of October or approximately 16-18 weeks.

Dissolved Gases

Dissolved oxygen (D.O.) concentration profiles at both stations were consistently above 9 ppm within both the epilimnion and the hypolimnion (Table 2). Whereas, oxygen levels were consistently above 90% saturation within the surface strata, D.O. levels within the hypolimnion decreased to as low as 66% during July and August of 1982. These percent saturation values may be somewhat low due to measurement error as the same depth (65 m) contained higher D.O. concentrations after this sampling period. The accuracy of the measurements during this period is questioned because the lake was well stratified by this time, and the dissolved oxygen (once reduced) could only be renewed by physical mixing with surface water, which did not occur. Nonetheless, the lake did exhibit in both years (especially in 1982), a slight hypolimnetic lowering of the oxygen concentration which appeared to be most pronounced within the lower strata of the deeper basin i.e., at Station 1.

General Water Quality Indicators

The primary cynosure of Falls Lake water quality regardless of depth is the lack of ions as indicated by an extremely low conductivity ($\sim$15 μmhos cm^{-1}), and a very low alkalinity ($\sim$7 ppm as $CaCO_3$) (Tables 3 and 4). In addition, the low alkalinity imparts little buffering capacity to the system resulting in the inability of the water to resist pH changes. However, the pH did remain fairly stable with few large scale variations either by season or with depth. Generally, the pH was observed to be slightly on the acidic side of neutral ($\sim$6.5) with low values around 5.5 and higher values slightly in excess of 7.5.

Calcium levels were found to be in the low to medium range for Alaskan lakes while magnesium levels were undetectable at <0.3-0.5 ppm, which is not an unusual occurrence for Alaskan waters. Iron levels in Falls Lake were higher than expected for clear water lakes ranging from 11 to 372 ppb, but are consistent with levels found in organically stained systems. Of particular interest is the increase in iron found to occur in the latter part of 1981 i.e., in late August (Table 3). This increase parallels the decrease in light penetration (Table 1) observed during the same time interval. In contrast, in 1982 when little change was observed in light

Table 2. The seasonal change in the concentration and percent saturation of oxygen within the epilimnion (1 m) and hypolimnion (65 m and 35 m) of Falls Lake during 1981 and 1982 at Stations 1 and 2 respectively.

	Dissolved Oxygen							
Station	1				2			
Depth	1 m		65 m		1 m		35 m	
Oxygen	Concentration	Saturation	Concentration	Saturation	Concentration	Saturation	Concentration	Saturation
Date	(mg L^{-1})	(%)	(mg L^{-1})	(%)	(mg L^{-1})	(%)	(mg L^{-1})	(%)
1981								
11/17	11.5	90	10.5	85	11.5	92	10.0	80
10/30	10.9	93	9.4	75	10.9	93	9.8	77
09/20	10.9	87	10.1	78	10.9	97	10.7	86
09/16	10.8	96	10.5	82	10.7	99	10.9	86
08/26	10.2	102	10.2	80	9.8	97	10.7	86
08/12	10.0	103	9.9	77	9.2	101	10.9	86
07/07	10.4	106	10.3	81	10.8	106	11.5	92
06/24	10.7	104	10.8	85	11.4	110	11.8	97
06/04	12.4	107	12.3	100	--	--	--	--
05/14	12.1	106	12.8	100	12.5	110	13.6	105
04/04	13.0	101	13.2	102	12.8	102	13.7	105
1982								
11/30	12.0	92	10.8*	82	12.2	92	11.4**	90
11/05	11.4	92	9.4*	75	9.8	80	11.6**	95
10/13	11.0	95	9.8*	77	9.8	85	9.4**	75
09/24	10.6	99	9.3	78	10.6	100	10.7	85
08/31	11.8	105	9.0	70	11.7	105	9.6	76
08/11	10.9	105	8.5	66	10.8	105	9.4	75
07/21	10.8	104	8.4	66	11.2	106	9.9	77
06/30	11.0	103	9.4	74	11.1	106	10.7	84
06/09	11.7	102	9.1	71	11.6	102	9.1	72
05/01	--	--	--	--	--	--	--	--

*46 m
**26 m

Table 3. The seasonal change of general water quality parameters and nutrient concentrations within the epilimnion (1 m) and hypolimnion (46 m and 26 m) of Falls Lake during 1981 at Stations 1 and 2 respectively.

Date/Depth	3/04		4/24				5/14				6/05				6/25				7/14			
Station	1		1		2		1		2		1		2		1		2		1		2	
Parameter	1 m	4 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m
Conductivity (μmhos cm^{-1})	14	14	21	20	20	20	28	25	22	21	14	14	14	14	21	21	24	21	21	21	21	44*
pH	6.3	6.1	5.9	5.9	6.1	5.9	6.3	6.5	6.4	6.4	6.3	6.2	6.2	6.2	5.6	5.6	5.6	5.6	5.6	5.7	5.7	4.3*
Alkalinity (mg L^{-1} as $CaCO_3$)	5	4	7	10	5	6	2	4	6	5	6	5	6	5	12	9	9	9	8	8	8	0 *
Calcium (mg L^{-1})	3.0	2.2	3.0	2.2	2.2	2.2	3.1	3.1	3.1	3.1	3.1	3.1	3.9	3.1	3.2	2.4	3.2	3.2	4.0	3.2	3.2	4.0
Magnesium (mg L^{-1})	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Iron (μg L^{-1})	42	46	58	68	30	53	30	108	66	77	101	41	66	34	57	27	42	51	84	11	15	130
Total Dissolved Solids (mg L^{-1})	---	25	---	---	---	---	---	---	---	---	11	---	---	---	---	---	11	21	---	31	---	32
Total Phosphorus (μg L^{-1} as P)	---	2.5	2.8	3.0	2.6	3.2	---	2.8	---	1.6	---	3.4	1.8	6.4	1.2	2.8	1.6	---	1.6	3.1	1.2	1.7
Total Filterable Phosphorus (μg L^{-1} as P)	2.2	1.7	1.2	1.3	1.3	1.2	2.1	1.0	4.6	1.4	3.7	1.0	1.2	0.6	0.7	2.9	2.5	2.5	3.5	3.5	1.1	3.2
Filterable Reactive Phosphorus (μg L^{-1} as P)	0.6	1.4	<0.5	0.6	0.6	0.6	1.0	1.0	5.2	0.7	1.4	0.8	1.1	0.5	0.7	1.5	0.9	---	1.6	1.5	0.4	0.9
Nitrate + Nitrite (μg L^{-1} as N)	35	41	37	40	32	33	25	36	25	34	12	42	14	37	5	42	<0.5	40	<0.5	41	<0.5	38
Ammonium (μg L^{-1} as N)	<0.5	3	18	4	3	6	8	10	8	8	8	12	0.6	4	16	11	6	9	10	13	5	8
Reactive Silica (μg L^{-1} as Si)	527	605	613	600	543	574	552	525	568	515	504	526	510	528	524	550	527	548	536	532	546	581

Continued

*Acid contamination

Table 3 continued. The seasonal change of general water quality parameters and nutrient concentrations within the epilimnion (1 m) and hypolimnion (46 m and 26 m) of Falls Lake during 1981 at Stations 1 and 2 respectively.

Date/Depth	8/13				8/27				9/17				10/01				11/02				11/20			
Station	1		2		1		2		1		2		1		2		1		2		1		2	
Parameter	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m
Conductivity (μmhos cm^{-1})	12	12	13	14	13	12	13	8	11	13	12	17	13	14	13	14	15	15	14	14	19	14	14	44
pH	6.2	6.1	6.2	5.9	6.3	6.1	6.1	6.0	6.9	6.1	6.2	6.0	6.5	6.4	6.6	6.5	6.5	6.4	6.5	6.4	6.9	6.6	6.6	7.7
Alkalinity (mg L^{-1} as $CaCO_3$)	7	6	6	3	6	4	6	4	16	6	6	5	6	6	6	6	7	6	6	6	11	7	7	23
Calcium (mg L^{-1})	2.5	1.7	2.5	2.5	2.5	2.1	2.5	1.7	2.1	2.5	2.1	1.7	2.1	2.5	2.1	2.5	2.5	2.1	2.1	2.1	2.5	2.5	2.5	8.3
Magnesium (mg L^{-1})	0.6	<0.5	<0.5	<0.5	0.6	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	1.1	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Iron (μg L^{-1})	72	36	95	46	160	53	80	34	157	189	225	67	271	75	288	59	85	53	173	52	316	372	308	281
Total Phosphorus (μg L^{-1} as P)	6.1	1.9	2.4	4.9	3.1	4.6	3.6	8.4	6.2	11.6	6.4	5.9	6.3	3.8	7.8	4.5	4.2	2.9	2.9	2.5	8.9	14.7	8.1	17.9
Total Filterable Phosphorus (μg L^{-1} as P)	1.4	2.7	1.7	1.2	2.7	2.2	2.7	7.3	3.2	1.6	1.6	10.5	2.2	---	2.2	1.7	2.4	3.8	1.8	2.4	2.6	1.5	3.9	2.8
Filterable Reactive Phosphorus (μg L^{-1} as P)	0.6	2.4	0.9	0.6	1.8	1.1	0.9	3.7	1.4	0.9	0.8	7.6	1.2	1.7	1.6	1.2	1.9	1.0	2.1	1.1	1.9	1.2	3.1	2.2
Nitrate + Nitrite (μg L^{-1} as N)	<2.0	30	13	47	7	52	10	27	17	31	6	44	17	43	14	37	27	52	24	38	35	40	34	35
Ammonium (μg L^{-1} as N)	7	17	14	10	10	13	8	11	9	13	3	26	9	11	5	6	19	29	6	8	5	9	5	4
Reactive Silica (μg L^{-1} as Si)	505	357	484	291	510	319	369	197	250	290	525	321	578	560	598	544	641	626	622	569	573	590	609	632

Table 4. The seasonal change of general water quality parameters and nutrient concentrations within the epilimnion (1 m) and the hypolimnion (46 m and 26 m) of Falls Lake during 1982 at Stations 1 and 2 respectively.

Date/Depth	5/01				6/09				6/30				7/23				8/12			
Station	1		2		1		2		1		2		1		2		1		2	
Parameter	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m
Conductivity (μmhos cm^{-1})	11	15	12	15	17	19	17	18	17	20	16	17	20	22	18	20	16	21	22	20
pH	6.5	6.8	6.5	6.9	6.8	7.3	6.7	6.7	6.5	5.9	5.7	6.6	7.7	6.3	6.8	6.5	7.5	6.6	8.3	6.6
Alkalinity (mg L^{-1} as $CaCO_3$)	3	7	4	7	6	6	6	6	4	4	6	6	7	6	7	7	7	7	7	6
Calcium (mg L^{-1})	1.5	2.2	1.5	2.2	7.2	7.2	7.2	7.2	7.2	7.3	7.2	7.2	2.1	2.5	2.5	2.5	1.7	2.1	2.5	2.5
Magnesium (mg L^{-1})	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	0.6	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Iron (μg L^{-1})	22	68	38	50	37	48	26	35	33	65	60	37	37	36	41	22	22	42	215	32
Total Phosphorus (μg L^{-1} as P)	1.4	5.7	0.8	1.6	6.3	3.5	2.8	2.8	3.6	4.2	4.3	3.7	3.9	4.7	4.1	4.6	3.5	4.5	3.3	4.6
Total Filterable Phosphorus (μg L^{-1} as P)	0.7	2.4	0.7	---	1.4	1.8	1.3	1.3	2.2	2.2	2.2	1.9	1.8	3.0	1.5	2.1	3.3	6.4	1.9	1.6
Filterable Reactive Phosphorus (μg L^{-1} as P)	0.6	2.3	1.2	---	1.5	1.8	1.2	1.4	1.5	2.1	1.4	1.2	1.3	2.5	1.2	1.2	1.3	1.8	1.2	1.1
Nitrate + Nitrite (μg L^{-1} as N)	22	57	30	---	19	19	17	48	12	54	11	44	10	46	<2	38	<2	47	<2	38
Ammonium (μg L^{-1} as N)	20	7	8	---	23	10	4	2	---	21	18	10	25	6	6	7	21	13	8	12
Reactive Silica (μg L^{-1} as Si)	169	623	315	613	618	533	---	562	256	698	523	593	441	604	481	565	392	608	440	557

Continued

Table 4 continued. The seasonal change of general water quality parameters and nutrient concentrations within the epilimnion (1 m) and hypolimnion (46 m and 26 m) of Falls Lake during 1982 at Stations 1 and 2 respectively.

Date/Depth	8/31				9/24				10/13				11/05				11/30			
Station	1		2		1		2		1		2		1		2		1		2	
Parameter	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m	1 m	46 m	1 m	26 m
Conductivity (μmhos cm^{-1})	20	21	---	20	18	21	19	20	18	21	18	20	20	21	19	19	21	20	20	18
pH	6.9	6.5	---	6.5	6.6	6.3	6.6	5.3	6.3	6.2	6.4	6.2	6.3	6.4	6.3	6.3	6.6	6.7	6.7	6.6
Alkalinity (mg L^{-1} as $CaCO_3$)	7	7	---	7	8	11	9	8	8	8	8	7	7	8	7	7	13	13	12	13
Calcium (mg L^{-1})	2.5	2.5	---	2.5	5.0	3.8	6.3	6.3	2.5	1.3	2.5	3.8	3.8	3.8	3.8	3.8	2.2	2.2	2.7	2.7
Magnesium (mg L^{-1})	<0.3	<0.3	---	<0.3	<0.3	1.4	1.4	1.4	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	0.8	1.4	<0.3	<0.3	<0.3	<0.3
Iron (μg L^{-1})	25	34	12	47	22	21	19	11	32	17	36	15	26	19	21	30	59	59	50	57
Total Phosphorus (μg L^{-1} as P)	4.8	4.8	3.9	5.1	6.9	7.6	6.0	4.3	8.7	6.7	8.1	9.0	3.2	2.8	3.5	3.1	6.1	4.9	4.4	6.4
Total Filterable Phosphorus (μg L^{-1} as P)	2.6	1.8	2.8	1.7	2.1	2.7	3.1	2.4	2.8	2.4	2.6	2.2	2.5	2.0	2.3	1.2	2.7	2.3	3.5	4.4
Filterable Reactive Phosphorus (μg L^{-1} as P)	1.7	1.3	2.2	1.1	1.2	1.2	1.5	1.4	1.7	1.2	1.4	1.1	1.2	0.9	1.3	1.2	1.3	1.3	1.4	2.0
Nitrate + Nitrite (μg L^{-1} as N)	<2	49	<2	38	4	59	<2	49	20	60	15	50	27	45	28	38	36	44	39	40
Ammonium (μg L^{-1} as N)	34	15	17	18	46	7	2	<1	7	2	3	2	32	10	16	4	12	5	4	2
Reactive Silica (μg L^{-1} as Si)	472	621	---	581	311*	232*	284*	233*	189*	268*	200*	250*	203*	243*	240*	222*	584	581	570	601

penetration over the entire ice-free period, iron levels remained unchanged as well (Table 4). The cause-and-effect relationship between high iron levels and decreased light penetration involved an intermediate, i.e., the yellow colored organic acids which stain the lake. These organic acids act as sequestering agents for iron thereby increasing its 'solubility' in oxygenated lake waters.

By imparting color to the water, the acids act to restrict light penetration to a few meters drastically reducing the volume of the trophogenic zone. In addition, these organic colloids selectively absorb light in the photosynthetically effective wavelengths thereby directly competing with algal pigments for energy. In the case of the organic colloids, the energy captured is released to the water as heat. Consequently, the upper layers of water are more quickly warmed, and reach higher seasonal temperatures than do clear water lakes. Thus, the degree of color imparted to a body of water by varying concentrations of organic colloids has important consequences on the ultimate productivity of stained lakes.

Nutrient Cycles

The algal nutrients of particular interest are carbon (alkalinity), phosphorus, nitrogen and silicon. Silicon levels were fairly low in Falls Lake, but were consistent with levels found in other Southeast Alaskan lakes. During 1981, silicon concentrations were in the 500-600 ppb range from April through July, and from October to November. However, in August and September, silicon levels dropped to ≤300 ppb (Table 3).

During 1982, silicon levels were again in the 500-600 ppb range with a trend for surface water values to be less than those found within the hypolimnion (Table 4). Again as in 1981, silicon levels were higher during the spring-summer period, and again in late November. During the September-early November period however, silicon levels dropped to approximately 200 ppb at all depths and stations sampled. However, some concern does exist on the reliability of these lower values because of the inadvertent freezing of the sample water during shipment to Soldotna.

Inorganic nitrogen levels for both years were found to be extremely low. In particular during 1981, ammonium concentrations were very low rarely exceeding 10 ppb within both the epilimnion and the hypolimnion at both stations (Table 3). In 1982, ammonium levels followed the same pattern as in 1981 being in the <10-20 ppb range for a majority of the sampling period. An exception was noted in that ammonium levels reached 30-50 ppb during late August and September within the surface strata at Station 1 (Table 4).

Nitrate + nitrite nitrogen prove to be the most reliable indicator of when nutrient utilization by the phytoplankton began to exceed nutrient supply. Nitrate nitrogen levels (with rare exception) remained at or below 50 ppb within all dates and depths sampled during both years of study. However, even within this narrow range (0-50 ppb) of concentrations, discernable trends were very evident and extremely important. During 1981, nitrate levels at both stations and within both strata (epilimnion and hypolimnion) were very similar during March through May (Table 3). However, even within the latter date a slight decrease in nitrate levels were observed in the epilimnion compared to those within the hypolimnion. This downward trend continued into early June, and by the end of June, epilimnetic nitrate concentrations were only 5 ppb at Station 1 and undetectable at Station 2, whereas hypolimnetic nitrate levels during this period remained unchanged. Thereafter, epilimnetic nitrate levels remained undetectable, and only became detectable again at both stations by the end of August. Nitrate concentrations then continued to rise through the beginning of October, reaching spring levels by the end of November.

In 1982, nitrate levels were again low (⩽50 ppb), but didn't reach undetectable levels within the epilimnion until late July to early August (Table 4). Prior to July, epilimnetic nitrate levels progressively decreased from early June to the end of June, and were less than that found within the hypolimnion. Undetectable nitrate concentrations were found within the epilimnion from late July through September, but in mid-October nitrate levels increased reaching spring levels by the end of November. Thus, for both years the period of nitrate depletion within the epilimnion lasted from the first part of June through the end of September and into early October.

Phosphorus levels are of critical importance because of the correlation between total phosphorus (total-P) loading and resultant primary production. In 1981, spring total phosphorus concentrations (taken during late April) equalled 2.9 ppb (Table 3). During the summer period, total-P levels found in the epilimnion were less than those found within the hypolimnion, except for the October and November samples. More importantly, total-P levels remained low within the epilimnion (at approximately 2.0 ppb) until the end of August. By the first part of October, epilimnetic total-P values had increased to greater than 7 ppb. After a decrease to less than 4 ppb during the first part of November, total-P levels again increased to greater than 8 ppb by the end of November.

In 1982, total-P levels were again low in early spring at <2 ppb, but increased to just under 4 ppb by the end of June, and then remained fairly constant until the middle of August (Table 4). Thereafter, total-P concentrations increased to over 8 ppb by the middle of October, but dropped to between 4-5 ppb by the end of the year. Thus, in both seasons of study, epilimnetic total-P concentrations peaked in late September/early October at 7-8 ppb which were four-fold the spring turnover values of ⩽2 ppb.

Inorganic phosphorus (estimated by filterable reactive phosphorus) was consistently detectable (i.e., ⩾0.5 ppb) within the epilimnion; however, concentrations were extremely low. During the spring of 1981, reactive phosphorus (reactive-P) levels were at the detection limit, but began to increase in mid-May to approximately 1 ppb (Table 3). This level was maintained through the end of August after which reactive phosphorus concentrations increased to above 1 ppb reaching 2.5 ppb by the end of November.

In 1982, epilimnetic reactive phosphorus levels within the spring period were very low (<1 ppb), but increased to slightly less than 1.5 ppb from early June through the middle of August (Table 4). At the end of August, reactive phosphorus levels increased to 2.0 ppb, but quickly dropped to just below 1.5 ppb by the end of September.

Nutrient Ratios

The ratio of inorganic nitrogen (ammonium + nitrate and nitrite) to total-P underwent considerable change in Falls Lake primarily within the epilimnion during the late spring to early fall period during both years of study (Table 5).

In 1981, the epilimnetic inorganic nitrogen (IN):total-P ratio at Station 1 began to drop by the 14 July sampling period to 14:1 (by atoms). Thereafter, the IN:total-P ratio remained below 14:1 until the beginning of November. During this same period, the hypolimnetic IN:total-P ratio remained consistently above 30:1 (except for the 17 September sample). At Station 2, a decrease in the IN:total-P ratio was observed in the first week of June which persisted below 14:1 until the first week of November, except for the 13 August sampling period. In contrast, within the hypolimnion the ratio persisted above 14:1 (except for 27 August). Thus, a lower IN:total-P ratio was found to occur at Station 2 earlier in the spring than was observed at Station 1, and, in addition, nutrient ratios were consistently lower at Station 2 within both the epilimnion and the hypolimnion.

In 1982, the same cyclic trends were noted as were found in 1981, except that the decrease in the IN:total-P ratio began later in the year. In particular, at Station 2 during June the nutrient ratio remained slightly above 14:1, but by the end of July had decreased below 5:1. In contrast, at Station 1 the ratio remained relatively high through the entire summer period, decreasing significantly below 14:1 only during the middle of October. At both stations within the hypolimnion, the ratio remained significantly above 14:1 for the entire year decreasing slightly at Station 2 during the middle of October. Thus, a lowering of the IN:total-P ratio within the epilimnion during the summer growing season appears to be a characteristic of the nutrient cycles within Falls Lake. Low IN:total P ratios were found to be particularly severe at Station 2, the shallower of the two stations.

Algal Biomass

The seasonal cycle of algal standing crop was estimated from the changing chlorophyll *a* (chl *a*) content. In addition, samples are currently being analyzed for algal densities by taxa, however, these results are not completed and cannot be presented at this time.

In 1981, chl *a* was extremely low at both stations averaging only 0.34 ppb at Station 1 and 0.44 ppb at Station 2 for the June through September period (Table 6). In general, there was a trend for the chl *a* content of the surface strata to be greater in early May and then decrease to seasonal lows during June through the middle of August. Peak chl *a* levels of 0.72 ppb were observed in May at Station 1, but occurred later at Station 2, reaching 0.63 ppb during September. After September, chl *a* levels declined to low levels reaching $\leq$0.20 ppb at both stations by the end of November.

Table 5. The ratio of inorganic nitrogen (ammonium + nitrate and nitrite) to total phosphorus concentrations (by atoms) within the epilimnion (1 m) and hypolimnion (46 m and 26 m) during 1981 and 1982 at Stations 1 and 2 respectively.

	Inorganic Nitrogen:Total Phosphorus (by atoms)			
	Depth			
Date	1 m	46 m	1 m	26 m
1981				
03/04	39:1*	--	--	--
04/24	44:1	32:1	30:1	27:1
05/14	--	36:1	--	58:1
06/05	--	35:1	17:1	14:1
06/25	39:1	42:1	8:1	--
07/14	14:1	39:1	9:1	60:1
08/13	3:1	55:1	25:1	26:1
08/27	12:1	31:1	11:1	10:1
09/17	9:1	8:1	3:1	26:1
10/01	9:1	31:1	5:1	21:1
11/02	24:1	62:1	23:1	41:1
11/20	10:1	9:1	11:1	5:1
1982				
05/01	66:1	25:1	105:1	--
06/09	15:1	18:1	17:1	40:1
06/30	14:1**	40:1	15:1	32:1
07/23	20:1	25:1	3:1	22:1
08/12	13:1	30:1	5:1	24:1
08/31	17:1	30:1	10:1	29:1
09/24	16:1	19:1	1:1	25:1
10/13	7:1	20:1	5:1	13:1
11/11	41:1	43:1	28:1	30:1
11/30	17:1	22:1	22:1	15:1

*4 m depth sampled
**Estimated ammonium concentration

Table 6. The concentration of chlorophyll *a* (chl *a*) and phaeophytin by date within the epilimnion (1 m) of Falls Lake during 1981 and 1982 at Stations 1 and 2.

	Station 1 (1 m)		Station 2 (1 m)	
Date	Chlorophyll *a* ($\mu g\ L^{-1}$)	Phaeophytin ($\mu g\ L^{-1}$)	Chlorophyll *a* ($\mu g\ L^{-1}$)	Phaeophytin ($\mu g\ L^{-1}$)
1981				
04/03	0.21	0.05	--	--
04/24	0.30	0.06	0.53	0.06
05/01	0.53	0.09	0.48	0.03
05/14	0.72	0.19	0.36	0.13
06/05	0.47	0.14	0.47	0.16
06/25	0.34	0.10	0.28	0.11
07/14	0.15	0.09	0.15	0.11
08/13	0.17	0.16	0.39	0.15
08/27	0.34	0.23	0.52	0.21
09/17	0.48	0.25	0.63	0.25
09/30	0.43	0.14	0.63	0.11
11/02	0.29	0.06	0.43	0.04
11/20	0.15	0.06	0.19	0.05
1982				
05/01	--	--	--	--
06/09	0.48	0.11	0.58	0.13
06/30	0.27	0.13	0.07	0.12
07/23	0.24	0.15	0.29	0.15
08/12	0.34	0.22	0.17	0.17
08/31	0.25	0.14	0.24	0.11
09/24	0.81	0.87	1.11	0.96
10/13	0.34	0.28	0.45	0.43
11/05	0.17	0.18	0.24	0.20
11/30	0.67	0.40	0.60	--

In addition to chl a being determined in surface samples, chl a was measured both at the middle and bottom of the euphotic zone. The latter two sampling depths changed depending on the degree of light penetration. Except for the early spring and late fall turnover periods, the highest chl a content was consistently found at the deeper depths. Thus, at Station 1 the chl a content of the water column increased with depth averaging 0.34 ppb at the top of the euphotic zone, 0.45 ppb at the mid-euphotic depth and 0.85 ppb at the bottom of the euphotic zone. The chl a content of the above profile was somewhat less than that observed at the shallower Station 2 where seasonal means increased to 0.40 ppb at the top of the euphotic zone, 0.71 ppb at the mid-euphotic depth, and 0.85 ppb at the bottom of the euphotic zone.

Comparing the surface seasonal mean chl a with the depth integrated seasonal mean, Station 1 averaged 0.34 ppb within the surface strata compared to 0.54 ppb as the depth integrated mean. Similarly, at Station 2 the seasonal mean chl a content increased from 0.40 ppb at the surface to 0.64 ppb as the depth integrated seasonal mean.

In 1982, samples were taken from the surface strata only (Table 6), and the chl a content found was again exceedingly low. Seasonal mean concentrations (June-September) equalled 0.40 ppb at Station 1 and 0.41 ppb at Station 2. Peak chl a levels were again found to occur in September at both stations reaching 1.1 ppb at Station 2, and 0.81 ppb at Station 1.

Comparing the two seasons, the chl a content was very similar i.e., at Station 1 chl a levels equalled 0.34 ppb in 1981 compared to 0.40 ppb in 1982, and at Station 2 chl a equalled 0.44 ppb in 1981 compared to 0.41 ppb for 1982 for the June-September period. Overall, the mean chl a content for the epilimnion during the June-September period in 1981 equalled 0.39 ppb, and for the same period in 1982 equalled 0.40 ppb.

Zooplankton

The zooplankton community of Falls Lake during 1981 and 1982 consisted of five species of macro-zooplankton; three cladocerans and two copepods. In addition to the macro-zooplankton, four genera of rotifer were found in 1982, but only three genera were observed in 1981.

During 1981 and 1982, the limnetic cladoceran community (in order of numerical abundance) consisted of *Bosmina longirostris, Daphnia longiremus* and *Holopedium gibberum* while the copepods were represented (in order of abundance) by *Diaptomus franciscanus* and *Cyclops vernalis* (Tables 7 and 8).

In terms of supporting a population of rearing sockeye fry there are three main characteristics of the zooplankton community of interest. First is the numerical abundance and relative species composition, second is the timing of zooplankton abundance versus the input of fry off the spawning beds, and third is the body-size of the macro-zooplankton.

The numerically dominate zooplankters during 1981 were the rotifers which comprised 63% of the community at Station 1 and 54% of the community at

Table 7. Seasonal density patterns of the zooplankton by taxa within Falls Lake during 1981 at Stations 1 and 2.

Station 1	Number/m2											
Date (1981)	03/04	04/22	05/13	06/04	06/24	07/12	08/12	08/26	09/16	09/30	11/29	11/18
Bosmina longirostris	1,931	173	792	1,216	4,292	15,729	35,150	44,575	35,660	5,349	10,914	3,948
Daphnia longiremus	576	474	1,212	1,027	1,146	2,101	2,904	2,929	2,993	650	3,235	2,382
Holopedium gibberum	0	0	0	211	313	2,738	1,681	2,165	0	0	0	0
Sub total (cladocera)	2,507	647	2,004	2,499	5,438	20,568	39,735	46,669	38,653	5,999	14,149	6,330
Cyclops vernalis	127	148	4,159	17,022	6,648	8,914	1,325	1,083	382	0	76	76
Diaptomus franciscanus	0	448	6,816	8,456	3,400	36,934	12,226	13,563	7,641	1,261	3,400	1,566
Subtotal (copepod)	127	596	10,975	25,478	10,048	45,858	13,551	14,646	8,023	1,261	3,476	1,642
Total macro-zooplankton	2,634	1,243	12,979	27,977	15,486	66,416	53,286	61,315	46,676	7,260	17,625	7,972
Kellicottia longispina	593	46	46	1,974	45,148	25,916	51,095	120,988	67,944	29,152	9,424	7,132
Conochiloides sp.	0	110	0	1,854	7,094	23,561	9,272	18,212	7,005	14,786	9,335	10,150
Asplanchna sp.	0	764	1,019	10,392	66,225	1,800	0	0	0	0	0	0
Keratella sp.	0	0	0	0	0	0	0	0	0	0	0	0

Station 2	Number/m2											
Date (1981)	03/04	04/22	05/13	06/04	06/24	07/12	08/12	08/26	09/16	09/30	11/29	11/18
Bosmina longirostris	--	703	474	1,999	4,419	6,724	29,674	28,681	34,437	53,986	18,938	4,376
Daphnia longiremus	--	382	428	509	866	1,528	2,292	4,585	2,394	2,292	3,184	1,149
Holopedium gibberum	--	0	110	713	993	2,038	2,738	2,038	509	0	0	0
Sub total (cladocera)	--	1,085	1,012	3,221	6,278	10,290	34,704	35,304	37,340	56,278	22,122	5,525
Cyclops vernalis	--	130	3,823	12,519	8,915	1,528	382	509	354	229	0	0
Diaptomus franciscanus	--	402	1,230	5,769	5,374	2,955	4,457	7,845	9,170	2,407	3,107	721
Sub total (copepod)	--	532	5,053	18,288	14,289	4,483	4,839	8,354	9,527	2,636	3,107	721
Total macro-zooplankton	--	1,617	6,065	21,509	20,546	14,773	39,543	43,658	46,867	58,914	25,229	6,246
Kellicottia longispina	--	64	614	509	5,145	21,982	74,312	32,603	51,604	28,655	10,405	2,015
Conochiloides sp.	--	46	955	89	0	2,955	13,118	16,658	52,674	25,217	12,545	4,040
Asplanchna sp.	--	537	8,574	2,241	2,700	8,151	0	0	0	0	0	20
Keratella sp.	--	0	0	0	0	0	0	0	0	0	0	0

Table 8. Seasonal density patterns of the zooplankton by taxa within Falls Lake during 1982 at Stations 1 and 2.

Station 1 Date (1982)	Number/m^2 05/01	06/06	06/30	07/21	08/11	08/30	09/24	10/13	11/05	11/30
Bosmina longirostris	683	446	1,191	1,962	3,923	12,545	14,888	6,559	3,821	7,642
Daphnia longiremus	1,363	1,191	1,083	942	1,682	1,274	2,318	637	2,930	2,191
Holopedium gibberum	0	0	249	510	866	1,911	268	0	0	0
Sub total (cladocera)	2,046	1,637	2,523	3,414	6,471	15,730	17,474	7,196	6,751	9,833
Cyclops vernalis	19	19	1,045	14,850	5,502	828	3,299	191	191	0
Diaptomus franciscanus	0	0	3,483	22,670	12,226	9,998	12,481	1,083	3,184	4,942
Sub total (copepod)	19	19	4,528	37,520	17,728	10,826	15,780	1,274	3,375	4,942
Total macro-zooplankton	2,065	1,656	7,051	40,934	24,199	26,556	33,254	8,470	10,126	14,775
Kellicottia longispina	211	300	1,274	2,471	43,811	71,765	137,914	178,490	152,191	90,169
Conochiloides sp.	0	0	0	331	6,979	14,200	63,296	44,957	66,862	76,618
Asplanchna sp.	764	408	4,368	16,455	77,280	37,952	3,834	0	191	0
Keratella sp.	0	0	0	0	357	0	0	0	1,274	153

Station 2 Date (1982)	Number/m^2 05/01	06/06	06/30	07/21	08/11	08/30	09/24	10/13	11/05	11/30
Bosmina longirostris	172	166	637	943	3,172	10,189	10,431	7,196	5,247	2,293
Daphnia longiremus	548	510	1,019	688	497	1,019	2,942	1,465	1,223	764
Holopedium gibberum	0	64	89	77	1,261	1,529	535	191	0	0
Sub total (cladocera)	720	740	1,745	1,708	4,930	12,737	13,908	8,852	6,470	3,057
Cyclops vernalis	38	38	1,490	14,952	2,408	713	268	191	0	0
Diaptomus franciscanus	0	0	2,586	12,226	5,960	1,529	1,159	828	1,529	2,560
Sub total (copepod)	38	38	4,076	27,178	8,368	2,242	1,427	1,019	1,529	2,560
Total macro-zooplankton	758	778	5,821	28,886	13,298	14,979	15,335	9,871	7,999	5,617
Kellicottia longispina	293	102	854	4,152	39,735	90,372	196,753	99,975	101,019	44,970
Conochiloides sp.	0	38	0	331	2,675	10,698	67,130	34,387	33,265	21,778
Asplanchna sp.	611	108	3,770	22,415	57,196	23,434	3,566	0	0	0
Keratella sp.	0	0	0	0	0	357	1,248	0	0	0

Station 2 (Table 7). Within the rotifers, the dominant organism was the herbivorous feeding *Kellicottia longispina* followed by *Conochiloides* sp., and then by the predaceous *Asplanchna* sp. The importance of the rotifers lies in their ability to compete directly with the herbivorous macro-zooplankton (principally *Bosmina*) for the smaller algal food particles. Of the macro-zooplankton, the smaller herbivorous *Bosmina longirostris* was the most abundant representing 49% of the community at Station 1, and 65% of the community at Station 2. *Daphnia* represented only 6% and 7% of the community, and *Holopedium* 2% and 3% at the two stations, respectively. Within the copepods, *Diaptomus* represented 30% and 15% of the macro-zooplankton, and *Cyclops* 12% and 10% at the two stations, respectively. Overall, the smaller (≤0.40 mm) herbivorous zooplankton represented by the rotifers and *Bosmina* formed 72% and 88% of the zooplankton found at Stations 1 and 2, respectively.

In regards to seasonal timing, the macro-zooplankton community consisted primarily of copepods from the beginning of May through the middle of July at Station 1, but only to the end of June at Station 2. Following the spring pulse of copepods (initially *Cyclops* followed by *Diaptomus*), the cladoceran component (principally *Bosmina*) became important. Bosminid domination of the macro-zooplankton lasted through the end of the year, but the peak of abundance occurred from July through the end of September. The importance of the above defined seasonal cycles lies in the continual replacement throughout the growing season of sequential peaks in zooplankter abundance.

In 1982, the zooplankton community consisted of the same species found in 1981 with the exception of an additional species of rotifer, *Keratella* sp. (Table 8). The rotifer community again dominated the zooplankton community representing 87% of the organisms found at Station 1 and 89% of those found at Station 2. Within the macro-zooplankton component, *Bosmina* again comprised the largest share of the community representing 32% of the organisms at Station 1, and 39% at Station 2. *Daphnia* represented 9% and 10% of the zooplankton at Stations 1 and 2, respectively while *Holopedium* represented only 2% and 4% of the community. *Diaptomus* represented 41% and 27% of the macro-zooplankton at the two stations, respectively compared to a 15% and 19% numerical contribution by *Cyclops*. Overall, the smaller (≤0.40 mm) herbivorous zooplankton represented by the rotifers and *Bosmina* formed 81% and 83% of the zooplankton found at Stations 1 and 2, respectively.

Comparing seasonal timing, the copepod component again was numerically important during the spring period at both stations followed by the cladoceran community which increased in importance later in the season. However in 1982, the *Diaptomus* component of the macro-zooplankton was exceptionally strong for most of the spring-summer period, but in turn the *Bosmina* component was exceptionally weak.

The third characteristic of interest to rearing fry is the body-size of the individual species. We use body-size within the cladoceran community as an indicator of a prey's visible size to the visual feeding sockeye fry. The seasonal mean (May-November) body-size of *Bosmina* at Station 1 during 1982 equalled 0.40 mm, of *Daphnia* 0.73 mm and of *Holopedium* 0.50 mm. Weighting the body-size by numbers of individuals per sampling period had little effect, as the seasonal mean body-size of *Bosmina* was slightly reduced to 0.37 mm, but the body-size of *Daphnia* and *Holopedium* remained unchanged. At Station 2 the body-size of *Bosmina* remained very low at 0.38 mm (0.36 mm), of *Daphnia* at 0.73 mm (0.72 mm), and *Holopedium* at 0.50 mm (0.51 mm) [comparing simple seasonal means with (weighted means), respectively].

Within the cyclopoid community the mean body-size of *Cyclops* at Station 1 was 0.80 mm (simple mean) compared to 0.66 mm using a weighted mean. Similarly, the body-size of *Diaptomus* equalled 1.06 mm compared to a weighted mean of 1.06 mm. At Station 2, the simple mean body-size for *Cyclops* equalled 0.69 mm compared to a weighted mean body-size of 0.57 mm, and for *Diaptomus* mean body-size equalled 0.95 mm while the weighted mean body-size equalled 0.78 mm. Thus, unlike the cladoceran community, the copepod components (*Cyclops* and *Diaptomus*) both had reduced body-sizes when simple seasonal means are compared with population size weighted seasonal means.

DISCUSSION

Within the two years of this pre-fertilization study (following one year of feasibility study), we have defined the pre-existing limnological state of Falls Lake. In addition, we have defined a need for nutrient addition, the quantity of nutrient to be added, the fertilizer's nutrient ratio, and the seasonal timing of its addition.

In summary, the basic chemical and biological features of the lake which point to the desirability of nutrient enrichment are as follows. During the first part of June the lake becomes thermally stratified and remains stratified until the middle of October. That is, a stable thermally defined epilimnion is present for approximately 16-18 weeks. During this period, the euphotic zone was found to lie entirely within the epilimnion, and, in general, to occupy a major portion of the epilimnetic volume except during the fall of 1981.

Nutrient utilization within the closely coupled epilimnetic/euphotic volumes was very strong leading to undetectable nitrate levels within the epilimnion during both years of study. In addition, we observed a decrease in epilimnetic silicon concentrations during periods of intense algal growth. Thus, we found evidence of inorganic nutrient depletion within the epilimnion which was especially severe at Station 2.

Finally, during both years of study, we found both the low inorganic nitrogen levels and low IN:total-P ratios within the epilimnion to coincide with the period of thermal stability i.e., from the first week of June to the beginning of October. This depletion of nutrients within the bulk of the epilimnion may account for the trend of greater chl a concentrations being found deep within the euphotic zone close to the top of the hypolimnion where inorganic nitrogen and silicon levels were significantly higher.

As we observed a strong utilization of algal nutrients, the extremely low level of algal biomass (chl a) indicated heavy grazing by the zooplankton. In turn, we found the zooplankton community to be dominated by herbivorous forms which numerically represented over 95% of the species/taxa found. In general, within the macro-zooplankton community the spring period tended to be dominated by the copepods (especially *Diaptomus*), while the late summer/ fall period tended to be dominated by the cladocerans (especially *Bosmina*). Overall, the zooplankton community consisted (70% to almost 90%) of small ($\leq$0.40 mm) body-sized organisms which are at the extreme lower size of prey available to rearing sockeye fry (Koenings 1983). That is, the existing zooplankton community is indicative of intense grazing pressure by predaceous rearing fry. Since the maximum temperature observed within the epilimnion was $\leq$16°C, we feel that rearing fry effectively foraged within the epilimnion during the entire growing season, and made very efficient use of the macro-zooplankton present within the entire epilimnetic volume. Finally, Falls Lake is similar to other oligotrophic lake systems we have studied e.g., Eshamy Lake in that nutrient levels (total-P), and chl a levels are extremely low. However, unlike Eshamy where the energy/biomass transfer ends within the zooplankton (and the lake possesses a zooplankton community indicative of low fish grazing pressure), the zooplankton community of Falls Lake is indicative of a more intense grazing pressure by rearing fry.

The severe grazing pressure on the zooplankton was particularly pronounced in 1982 when rotifers represented between 87% and 89% (by station) of the zooplankton found, compared to 1981 when rotifers represented from only 54% to 63% of the zooplankton. In particular, in 1982 when the rotifers were very abundant (seasonal mean densities ranging from 86,000 organisms/m^2 to 109,500 organisms/m^2), the *Bosmina* population was very weak, representing only 4% of the zooplankton community (seasonal mean densities ranging from 4,100 organisms/m^2 to 5,400 organisms/m^2). In 1981, when the rotifer population was relatively depressed (seasonal mean densities from 33,800 organisms/m^2 to 54,000 organisms/m^2), the *Bosmina* population was relatively strong, representing from 18% to 30% of the zooplankton or from 15,800 organisms/m^2 to 18,400 organisms/m^2. Thus, it appears that when *Bosmina* populations are reduced by predation from rearing fry, rotifer numbers expand. Conversely, the argument can be made that when the rotifer community is favored by environmental conditions the *Bosmina* population is considerably reduced through competition for a limited food supply. However, given the extremely small body-size of the *Bosmina* (and other species of macro-zooplankton) we feel that the evidence suggests a causal mechanism of heavy predator (fish) pressure on the entire macro-zooplankton community. That is, the heavy grazing pressure on the macro-zooplankton by rearing fry releases the rotifers from direct competition for food and allows them to expand in number.

Falls Lake Nutrient Loading

The present loading of phosphorus into Falls Lake equals 313 mg P/m^2/yr compared to a critial loading rate of 1,043 mg P/m^2/yr. Thus, Falls Lake is presently at 30% of critical loading. We plan to increase the loading rate an additional 40% to give an overall yearly loading of 70% of critical.

Our target loading is thus defined as 70% of critical loading or 730 mg P/m^2/yr. This leaves 417 mg P/m^2/yr to be provided by the inorganic fertilizer: a total of 430 kg of phosphorus.

The fertilizer to be used is a special blend of a liquid product (27-7.6-0) containing 27% nitrogen, 7.6% phosphorus (as P_2O_5) and 0% potash (18:1 N:P atom ratio). The material weighs approximately 5.44 kg/gal or 0.18 kg of phosphorus per gallon. Thus, we require 430 kg of phosphorus to be provided by the fertilizer which contains 0.18 kg of phosphorus per gallon or 2,389 gallons of product in 30 gallon barrels i.e., approximately 80 barrels of fertilizer.

From our limnological studies, we found that Falls Lake has a stable thermal structure, coinciding with nutrient depletion within the epilimnion, from the first part of June until mid-October, or a period of 18 weeks. We feel fertilization should begin on or about June 1st and extend until at least mid-October for a fertilization period of 18 weeks. Thus, we have 18 weeks to add 80 barrels of fertilizer with additions taking place every 10 days. By using a 10 day application series we have defined 13 applications per season or 6 barrels to be added every 10 days.

The actual application of product should avoid the littoral zone and be confined to the northwest and southwest limnetic section of the lake (Figure 3) immediately adjacent to observed sockeye spawning areas. Finally, as the sampling design calls for a three-week rotation, water samples should be taken prior to every other fertilization period i.e., fertilization application every 10 days with water quality sampling taking place every 20 days.

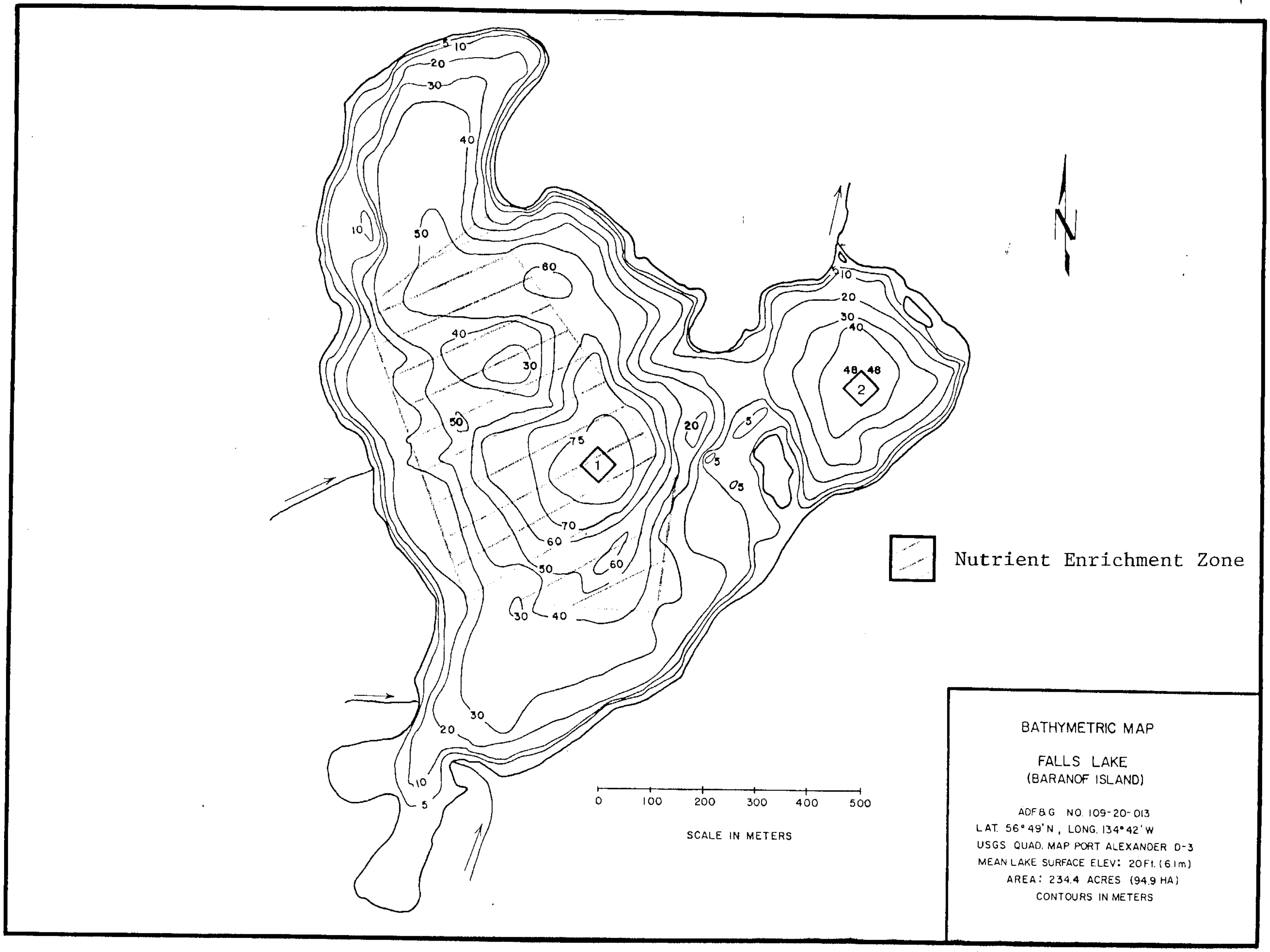

Figure 3. Morphometric map of Falls Lake with the recommended fertilizer application zone in relation to the location of the limnological sampling Stations 1 and 2.

RECOMMENDATIONS

1) Apply inorganic fertilizer (high N:P atom ratio) at a rate that will result in an increase in the phosphorus loading from 30% to 70% of critical.

2) Fertilizer addition should begin no earlier than the first week of June and last until the first part of October.

3) Closely monitor the inorganic nitrogen (and silicon) levels in order to prevent a further lowering of the inorganic nitrogen:total-P ratio.

4) Continue the detailed limnological monitoring in order to assess the impact of the increased nutrient loading on the capacity of Falls Lake to rear sockeye fry.

ACKNOWLEDGEMENTS

We wish to thank the U. S. Forest Service personnel, in particular, Mike Scott, Scott Russell, and Bob Vaught for technical assistance in all phases of the Falls Lake project. In addition, we would like to thank the Alaska Department of Fish and Game field personnel for their considerable help in making this project possible.

Finally, we gratefully acknowledge the time and effort of Bob Burkett, Chief of Technology and Development, and the U. S. Forest Service without whose program direction and funding respectively the Falls Lake project would not have been possible.

REFERENCES

Brooks, J. L. 1957. The systemetics of North American *Daphnia*. Mem. Conn. Acad. Arts Sci. 13:1-180.

Edmondson, W. T., and G. G. Winberg (eds.). 1971. A manual for the assessment of secondary productivity in fresh waters. International Biological Program Handbook. 12:358 p.

Eisenreich, S. J., Bannerman, R. T., and D. E. Armstrong. 1975. A simplified phosphorus analysis technique. Environ. Letters 9:43-53.

Haney, J. F., and D. J. Hall. 1973. Sugar coated *Daphnia*: A preservation technique for cladocera. Limnol. Oceanogr. 18:331-333.

Harding, J. P., and W. A. Smith. 1974. A key to the British Freshwater cyclopid and calanoid copepods. Sci. Publ. Freshwater Biol. Assoc. 18:1-54.

Hutchinson, G. E. 1957. A Treatise on Limnology: Vol. I. Geography, Physics and Chemistry. John Wiley and Sons, N. Y. 1015 p.

Koenings, J. P., Altland, B., Edmundson, J. Tobias, T., and D. Seagren. 1980. Alaska Department of Fish and Game Limnology Field and Laboratory Manual. (In review).

_______________ and D. Barto. 1981. Lake Enrichment Feasibility Lakes: Northern Southeast Alaska (In review). 52 p.

_______________. 1983. Limnology investigations at Bakewell Lake (1981-1982) and at Badger Lake (1982). Alaska Department of Fish and Game, F.R.E.D. Division Technical Report Series No. 5. 28 p.

Murphy, J. and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chem. Acta. 27:31-36.

Pennak, R. W. 1978. Fresh-water invertebrates of the United States, 2nd edition. John Wiley and Sons, New York. 803 p.

Reimann, B. 1978. Carotenoid interference in the spectrophotometric determination of chlorophyll degradation products from natural populations of phytoplankton. Limnol. Oceanogr. 23:1059-1066.

Stainton, M. P., Capel, M. J., and F. A. J. Armstrong. 1977. The chemical analysis of freshwater, 2nd ed. Fish. Mar. Serv. Misc. Spec. Publ. 25:1-166.

Strickland, J. D. H., and T. R. Parsons. 1972. A practical handbook of seawater analysis, 2nd ed. Fisheries Research Board of Canada Bulletin. 167:310 p.

Wilson, M. S., and H. C. Yeatman. 1959. Free-living copepoda. pp 735-861. In: W. T. Edmondson [ed.], Fresh-water biology, 2nd ed. John Wiley and Sons, Inc. 1248 p.